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STRAPDOWN NAVIGATION COMPUTER STUDIES

Final Report

Contract No. NAS 9-9705

MARCH 1970 -

Prepared for NATIONAL AERONAUTICS AND SPACE ADMINISTRATION MANNED SPACECRAFT CENTER HOUSTON, TEXAS

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TABLE OF CONTENTS

Chapter			Page
1	INTRO	DDUCTION	1
2	CONF	GURATION AND COMPONENT TECHNOLOGY FOR A STRAPDOWN COMPUTER	2
3		ERSION METHODS FOR TRANSFORMATION FROM DODECAHEDRON TO D AXES	11
	3.1	Direct Realization by Use of Pseudo-Inverse and Status Matrices 3.1.1 Theoretical Analysis of Approach 3.1.2 Implementation of Pseudo-Inverse and Status Matrices Method Using LSI Packaged Basic Elements	11 11
	3.2	Conversion from Dodecahedron to Triad by Sensor Correc-	
	c	tion 3.2.1 Description 3.2.2 Parity Integration 3.2.3 Constant Rate Multiplier	18 18 25 29
4	TWE	EMENTAL COMPUTER CONFIGURATION FOR A REDUNDANT CMG CON-	
-1		SYSTEM	35
	-	Introduction General Description of the CMG Control System 4.2.1 The CMG Configuration 4.2.2 CMG Steering Laws 4.2.3 The Rate Gyro Configuration 4.2.4 Control Computer Description	35 35 35 37 40 45
	4.4	4.2.5 Fail-Operational Computation Steering Law Computations 4.3.1 Equations and Computer Structure 4.3.2 Incremental Computation 4.3.3 The ΔA Computation 4.3.4 The ΔB Computation 4.3.5 The ΔC Computation 4.3.6 The ΔC Computation 4.3.7 The ΔD Computation 4.3.8 The Δu Computation 4.3.9 The Δu Computation 0ther Computations 4.4.1 Thial Conversion 4.4.2 Failure Monitoring and Mode Control	49 51 58 59 66 70 72 72 76 81 81 85
	4.5	Conclusions and Recommendations	86
5	SIMU	DIRECTION COSINE SIMULATION PROGRAM FOR CHECKOUT RUNS	88
	5.1	Description of Method and Results	88

TABLE OF CONTENTS (cont)

Chapter		<u>Page</u>
•	5.1.1 Types of Runs 5.1.2 Results 5.2 Program Description	. 88 . 88 90
	APPENDIY A _ Smooth Pulse Sequences	

LIST OF ILLUSTRATIONS

<u>Figure</u>		Page
2-1	Block diagram of SIMU computer.	3
2-2	Resolver direction cosine unit.	5
2-3	Sequencing of all-resolver cosine computer.	5
2-4	TMR resolver.	10
3-1	Incremental input encoding for the six-gyro system	14
3-2	Block diagram of six-gyro system using pseudo-inverse and status matrices method.	19
3-3	Block diagram of sensor correction method.	19
3-4	Dodecahedron gyro correction resolver.	22
3-5	Triad axis generator.	24
3-6	DDA solution.	26
3-7	Parity integrator.	27
3-8	Pulse rate multiplier.	30
3-9	Continued-fraction pulse rate multiplier.	33
4-1	Model of the Sperry 6-GAMS configuration.	36
4-2	CMG configuration reference system	36
4-3	Dodecahedron axis system.	41
4-4	Three-variate control law.	47
4-5	Six-variate control law.	47
4-6	CMG control system block diagram.	50
4-7	Method of failure detection.	50
4-8	Organization of the pseudo-inverse steering law computer.	53
4-9	Basic incremental computer elements.	60
4-10	Incremental multiplier.	60

LIST OF ILLUSTRATIONS (cont.)

<u>Figure</u>		Page
4-11	ΔA computer.	61
4-12	ΔB computer.	67
4-13	ΔC computer.	71
4-14	Δd _o computer.	73
4-15	ΔD computer.	74
4-16	Δu computer.	77
4-17	$\Delta \overset{\cdot}{c}$ computer.	79
5-1	Plot of error in repeatability.	89
5-2	Flow charts of simulation program.	91
5-3	Card input format.	96

LIST OF TABLES

<u>Table</u>		Page
2.1	Direction Cosine Orthogonality Conditions	6
2.2	Direction Cosine Covering by Orthogonality Equations	7
3.1	Twenty Five Required Data-Word Natrix	12
3.2	Status Matrices	15
3.3	Failure Detection Parity Equations.	20
3.4	Table for Substitution in General 1-Gyro Restoring Equation	21
3.5	Table of Binary Constants for Dodecahedron Gyro Correction	23
3.6	$E_{\hat{\mathbf{j}}}$ Subset for $\lambda_{\hat{\mathbf{i}}}$	28
3.7	Comparison of Resolution of Resolver and Continued Fraction Rate Multipliers.	34
5.1	SIMU Simulation Data	90
5.2	Results of SIMU Simulation Program for Checkout Runs	97
5.3	Oscillatory Runs - Ten Cycles O to 1024 Pulses and Return to O Again	115
5.4	Program Listing	122

CHAPTER I

The text which follows constitutes the final report on work performed at the Sperry Rand Research Center (SRRC) under contract NAS 9-9705 with the NASA Manned Spacecraft Center, Houston, Texas. The objectives of this program were twofold. First, it was to consider optimum organization and component technology for a strapdown transformation computer based upon the assumption of gyroscope and accelerometer inputs denoting components of angular and velocity change measured about an orthogonal axis triad. Second, it was to treat optimum methods of implementing a reliable attitude reference or control system when the gyroscope and accelerometer inputs were redundant and configured about the six normals to faces of a dodecahedron.

The work which is reported here divides into four major activites, each corresponding to a chapter. These will be described briefly. The first part of the activity, described in Chapter 2, is a study of means whereby a strapdown computer such as the one constructed for laboratory use under a previous contract may best be organized and implemented in reliable, flight-ready form. The second activity, covered in Chapter 3, is an investigation of optimum means for performing attitude reference computations when redundant dodecahedron sensor arrays are utilized. The third part of the study, described in Chapter 4, is a study of an attitude control system employing redundant control moment gyros as actuators. This part of the work was performed at the Sperry Flight Systems Division, under subcontract to SRRC. The final part of the study, Chapter 5, contains the results of further computer simulations of the truncation-error-free direction-cosine computation used in SIMU, methods and results are described.

CHAPTER 2

CONFIGURATION AND COMPONENT TECHNOLOGY FOR A STRAPDOWN COMPUTER

In a previous contract a strapdown coordinate-conversion computer was designed and constructed which used a truncation-error-free algorithm to compute direction cosines relating a rotating-axis system to one which was inertially stabilized. The organization of this computer was based upon a building block concept in which most blocks were digital accumulators with overflow detection and ternary input gating. In the present study, where the goal is to determine optimum system organization and component technology for such a computer, several structures, including the accumulator block, were studied.

Before describing the system, the underlying reasons for the particular choice of implementation will be given. First of all, since discussion centers about a spaceborne computer, weight, volume and power must be minimized and reliability must be maximized. From the point of view of weight, volume and power, it is clear that minimality is provided by incorporating as high a level of circuit integration as is feasible within the constraints of present day technology. Studies have shown that maximizing the level of integration also provides the greatest reliability, since circuit bonds and off-chip interconnections, which are the primary sources of failure, are minimized. At the present time, reasonable device yields are obtained for integrated circuit chips with dimensions of 120 mils on each side. Interline spacings of 0.1 mil are readily obtainable. For metal-oxide-silicon (MOS) circuitry, active device areas are approximately 1.0 mil square. Allowing for metallization patterns and bonding pads, this means that an active device count of 2000 to 5000 is reasonable for MOS integrated circuits. Four-phase or ratioless MOS circuitry allows transfer rates from 2 to 5 WHz to be realized, and provides the highest circuit density presently available. For this reason, the preferred mechanization of the strapdown computer would use four-phase MOS LSI.

As in most applications, cost is also of importance. Development and manufacturing costs for the strapdown computer can be reduced by limiting the number of different chip types required. For this reason and the reasons above, the approach which was followed in formulating the systems structures was one in which maximum use was made of the fewest possible different circuit types, while maintaining the highest level of integration consistent with present technology and while trying to minimize the number of interconnections between chips.

The block diagram assumed for the triad system is shown in Fig. 2-1. It is essentially that of the SIMU computer, except that sections intended primarily for laboratory use have been eliminated. A set of three signals from orthogonal triad gyroscopic sensors provides the input to the direction cosine computation. These signals are assumed to be corrected for drift scale factor errors by equipment preceding the navigation computer. The gyro inputs are added in the buffer to triad rotational rate commands. These commands replace the earth-rate correction system in the SIMU computer and are assumed to be generated by the main guidance and navigation computer. They enter the strapdown computer referred to stable coordinates and are transformed to rotational coordinates by the "commanded rate transformation" unit. Triad strapdown accelerometer signals are transformed to stable coordinates by the "AV

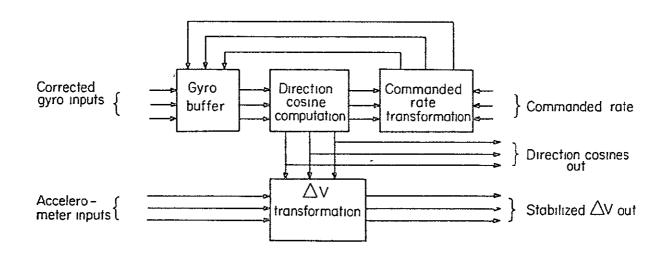


FIG. 2-1 Block diagram of SIMU computer.

transformation" unit, as in SIMU. System outputs are the stabilized $\Delta V^{\dagger}s$ and the nine direction cosines.

Besides the configuration used in the SIMU computer, a new form has been developed for system implementation. This will be described first, and then methods for increasing system reliability will be discussed for both cases.

The new method of organization is very similar in form to SIMU except that 16-bit digital resolvers are used for the direction cosine computation instead of the accumulators. A diagram of one of the three identical direction cosine units is shown in Fig. 2-2. Each direction cosine resides in a triple of resolvers, the Y resolver storing the upper 16 bits, the R resolver storing the middle 16 bits, and the E resolver storing the lower 16 bits.

The updating algorithm used is the original truncation-error-free method involving three passes. The operations for a θ_{κ} pulse are specified by the matrix equation

$$M_{X} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1-h^{2} & 0 \\ 0 & 0 & 1-h^{2} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & h \\ 0 & -h & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & h \\ 0 & -h & 1 \end{bmatrix}$$
(2.1)

Similar operations hold for $\,\theta_{_{\mathbf{Z}}}\,$ and $\,\theta_{_{\mathbf{Z}}}$.

Each of the resolvers is equipped with its own serial adder operating in a closed loop Thus, simultaneous accumulation by all resolvers is allowable. with the storage register By judicious sequencing of operations, a three-to-one speedup in processing rate is obtained over the originally proposed SIMU computer. This sequencing is best clarified by means of the schedule shown in Fig. 2-3. Each term in the schedule signifies the updating of the contents stored in the specified resolver by adding to it the contents of another resolver, as determined by the updating matrices. The superscripts indicate whether it is the x-, y-, or z-matrix equation, and the priming of the superscripts specifies the right, middle, or left matrix, respectively. Thus, $E_1^{y'}$ indicates the updating of resolver E_1 for the second pass of θ_y updating. This updating involves subtracting the contents of resolver R_3 from the contents of resolver E_1 and storing the difference in E_1 . It is clear that the updating for x, yand z pulses of any rank of resolvers (say, the E resolvers) requires just nine word-times. Since overlapping of cycles is allowable, a new set of gyro pulses may be entered every nine word-times. If the clock used is the same as in the SIMU computer, a processing rate speedup of two-to-one over SIMU is obtained The speedup over the originally proposed system is threeto-one. Besides the speedup in processing rate (or, conversely, the ability to use a lower clock rate), another advantage of this form of implementation is that it provides greater uniformity of components throughout the system, since the resolvers used in the cosine computation are identical to those used to provide the cooldinate transformations elsewhere in the system. An appropriate circuit embodiment would be the realization of one or more resolvers as a single integrated circuit. The approximate device count for a simplex realization of such a circuit is 350 transistors, so that such an embodiment is quite feasible using MOS/LSI technology.

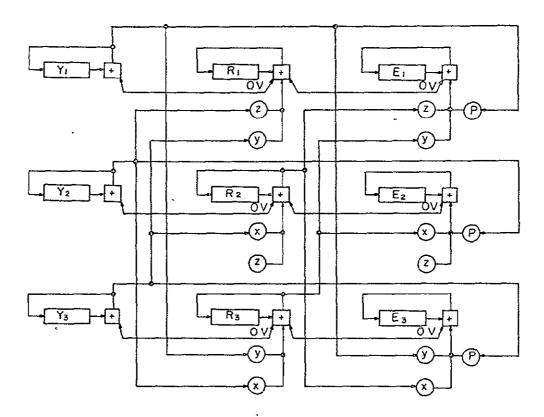


FIG. 2-2 Resolver direction cosine unit.

FIG. 2-3 Sequencing of all-resolver cosine computer.

Several techniques have been investigated for increasing reliability over the "simplex" SIMU computer. These will be described, although no revolutionary developments have emerged. The first technique makes use of the orthogonality properties of the direction cosine matrix for self checking. If C is the cosine matrix and C^T is its transpose, then orthogonality implies that

$$\mathbf{c} \cdot \mathbf{c}^{\mathrm{T}} = \mathbf{c}^{\mathrm{T}} \cdot \mathbf{c} = \mathbf{1} \tag{2.2}$$

where I is the identity matrix. Carrying out the term-by-term multiplications, the twelve distinct equations in Table 2.1 result.

TABLE 2.1
Direction Cosine Orthogonality Conditions

Eq. No.	Equation
1	$c_{11}^2 + c_{12}^2 + c_{13}^2 - 1 = 0$
2	$c_{11}c_{21} - c_{12}c_{22} + c_{13}c_{23} = 0$
3	$c_{11}c_{31} + c_{12}c_{32} + c_{13}c_{33} = 0$
4	$c_{21}^2 + c_{22}^2 + c_{23}^2 - 1 = 0$
5	$c_{21}c_{31} + c_{22}c_{32} + c_{23}c_{33} = 0$
6	$c_{31}^2 + c_{32}^2 + c_{33}^2 - 1 = 0$
7	$c_{11}^2 + c_{21}^2 + c_{31}^2 - 1 = 0$
8	$ c_{11}c_{12} + c_{21}c_{22} + c_{31}c_{32} = 0 $
9	$c_{11}c_{13} + c_{21}c_{23} + c_{31}c_{33} = 0$
10	$c_{12}^2 + c_{22}^2 + c_{32}^2 - 1 = 0$
11	$ c_{12}c_{13} + c_{22}c_{23} + c_{32}c_{33} = 0 $
12	$c_{13}^2 + c_{23}^2 + c_{33}^2 - 1 = 0$

The failure of some subset of the equations in Table 2.1 to be satisfied may be used as a form of parity check to determine faulty computation of the direction cosines. For instance, an error in C_{11} alone is indicated by lack of satisfaction of Eqs. (2.1) and (2.7). Similar criteria may be derived from the covering relationships expressed by Table 2.2. At "X" at

the intersection of a particular column and row indicates that the cosine corresponding to that row is covered by the equation corresponding to the column.

TABLE 2.2

Direction Cosine Covering by Orthogonality
Equations (see Fig. 2-1)

	Equation											
Cosine	1	2	3	4	5	6	7	8	9	10	11	12
c ₁₁	х	х	X				x	X	X			
c ₁₂	х	X	X					x		X	X	
C ₁₂ C ₁₃ C ₂₁ C ₂₂ C ₂₃ C ₃₁ C ₃₂ C ₃₃	х	X	X						X		X	x
c ₂₁		X		x	X		X	X	X			
c ₂₂		X		x	X			X		X	X	
c ₂₃		X		X	X				X		X	X
C ₃₁			X		X	X	X	X	X			
c ₃₂ \			X		X	x		X		X	X	
c ₃₃			X		X	X			X		X	X

If a single bit error is introduced into one of the direction cosines, say \mathbf{C}_{11} , the error will propagate to cosines \mathbf{C}_{12} and \mathbf{C}_{13} as a function of angular input increments received. No error, however, will propagate to the other cosines, since their computation "loops" do not intersect those of \mathbf{C}_{11} . The dependence of \mathbf{C}_{12} , for instance, upon \mathbf{C}_{11} may be expressed by the partial differential equation pair below

$$\frac{\partial c_{11}}{\partial \theta_z} = -c_{12} \tag{2.3}$$

$$\frac{\partial c_{12}}{\partial \theta_z} = c_{11} \quad . \tag{2.4}$$

Consider the inversion of a single bit in the representation of C_{11} and its effect upon C_{12} . The bit inversion will be equivalent to adding some quantity S to C_{11} . Let the error in C_{11} be E_1 and the error in C_{12} be E_2 . Then

$$\frac{\partial C_{11}}{\partial \theta_z} + \frac{\partial E_1}{\partial \theta_z} = -C_{12} - E_2 \tag{2.5}$$

$$\frac{\partial C_{12}}{\partial \theta_{z}} + \frac{\partial E_{2}}{\partial \theta_{z}} = C_{11} + E_{1}$$
 (2.6)

with initial values

$$E_1 = S$$

$$E_2 = 0$$
.

Subtracting left and right equivalents from this set, the resulting error equations are

$$\frac{\partial E_1}{\partial \theta_2} = -E_2 \tag{2.7}$$

$$\frac{\partial E_2}{\partial \theta_2} = E_1 \tag{2.8}$$

with the obvious solution

$$E_1 = S \cos \theta_z \tag{2.9}$$

$$E_2 = S \sin \theta_2 \tag{2.10}$$

If the checking equations of Table 2.1 are solved at fixed intervals and involve the upper in bits of the cosines, then the maximum period between solutions such that a single bit error in one of the direction cosines can be detected before it affects the other cosines in its loop is a function of in and the maximum angular rate which the system can accommodate. If the worst case bit inversion (i.e., S=1) is assumed, the maximum period between solutions is set by the inequality below, where ω_{max} is the maximum angular velocity and T_{max} is the maximum period

$$T_{\text{max}} \le \frac{1}{\omega_{\text{max}}} \sin^{-1} 2^{-n}$$
 (2.11)

After detecting the cosine which is in error, the problem of what to do about it still remains. If the angles were unchanging, it would be a simple matter to recompute the correct values of the cosines using the relationships of Table 2.1. This, however, is not generally the case. One possibility is to retain in storage at some point the last complete set of correct cosines computed before the error was detected. These values can be reinserted and the computations restarted. Although this method introduces an overall error if vehicle attitude has changed during the time since restart values were observed, the amount of error can be limited if the checking equations are run frequently enough. Another method which leads to no

error accumulation is to stop the direction cosine computations as soon as an error is detected and store the input angle increments in a buffer, maintaining the proper sequence among the three axes. The equations in Table 2.1 then can be used to restore the proper value to the faulty cosine, after which the stored input increments are utilized to update the cosine matrix to its proper value. This method will succeed only if the allowable updating rate of the cosine matrix is greater than the maximum allowable pulse input rate from the gyros.

In the event that the error is caused by permanent failure of one of the components within the direction cosine computer, more than one-time correction will be required. A possible solution to this situation is obtained by noting that the nine cosines are computed as three independent triads. If a spare triad computer is included and is equipped with the proper connections to allow its output to be switched to replace any of the three primary computer outputs, then upon detection of a failure in one of the three primary units the restart operation can involve the spare unit, after which it is switched into the system in place of the faulty element.

In the methods described above that make use of the orthogonality properties of the direction cosine matrix for self correction, the nature of the computations and their rate is such that corrections can be handled by the general purpose guidance computer associated with the system. It is possible, and also more straightforward, to include logical redundance within the direction cosine computer itself rather than using external means. In both the SIMU and all-resolver systems, numerous computational feedback loops are used. If it is desired that the addition of redundancy will effect correction of transient errors as well as permanent component failures, it is advisable to add the redundancy in such a way that error correction occurs within all feedback loops. One scheme for providing this sort of correction is shown in Fig. 2-4, which depicts a triply modular redundant resolver. Voting circuits are introduced in such a way that they intersect the tightest feedback paths and still provide correct outputs from all three of the resolver segments for the maximum number of component failures within the segment.

It is difficult to supply all-inclusive arguments for the level at which redundancy should be introduced in the strapdown computer, but since the resolver is the element which seems best suited for use as the basic building block, larger or smaller elements not providing the same lead-count and circuit-type minimality, and since the packaging of three interconnected resolvers with voting elements on a single substrate is presently within the state of the art, this configuration is recommended as the form to be used for implementation of the strapdown computer.

REFERENCES

1. "Failure Rate/Temperature Data for Univac Military Computers," Univac Federal Systems Division, Publication PX-4388-2, July 1969.

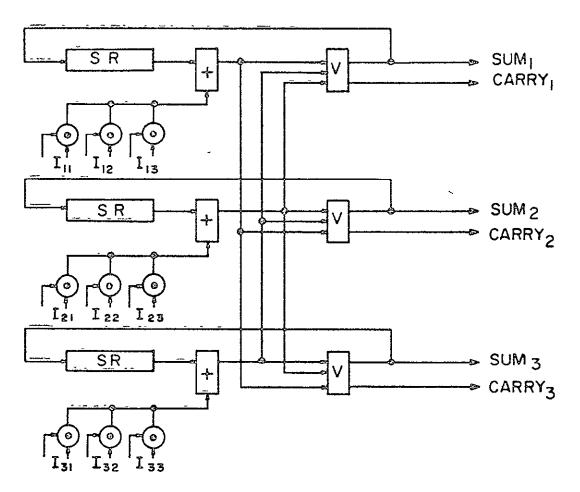


FIG. 2-4 TMR resolver.

CHAPTER 3

CONVERSION METHODS FOR TRANSFORMATION FROM DODECAHEDRON-TO-TRIAD AXES

3.1 DIRECT REALIZATION BY USE OF PSEUDO-INVERSE AND STATUS MATRICES

3.1.1 Theoretical Analysis of Approach

In this part of the report we describe a method of transforming the six-vector

$$m = \begin{pmatrix} m_{a} \\ m_{b} \\ m_{c} \\ m_{d} \\ m_{e} \end{pmatrix}$$

$$(3.1)$$

of the dodecahedron reference system into the three-vector

$$\mathbf{b} = \begin{pmatrix} \mathbf{b}_{\mathbf{X}} \\ \mathbf{b}_{\mathbf{y}} \\ \mathbf{b}_{\mathbf{z}} \end{pmatrix} \tag{3.2}$$

of the orthogonal triad reference system.

The geometric relationship between the two systems is given by

$$m = Hb ag{3.3}$$

where

$$H = \begin{bmatrix} S & 0 & C \\ -S & 0 & C \\ C & S & 0 \\ C & -S & 0 \\ 0 & C & S \\ 0 & C & -S \end{bmatrix}$$
(3.4)

$$S = s_{1n}\alpha = \sqrt{\frac{5 - \sqrt{5}}{10}}$$
 (3.5)

$$C = \cos \alpha = \sqrt{\frac{5 + \sqrt{5}}{10}} \tag{3.6}$$

Since every 3 × 3 submatrix of H is nonsingular, any three out of the six equations of (3.3) can be used to determine the b components in terms of the corresponding three components of m. The nature of the problem, however, is such that the instruments providing the components of m are subject to errors and, as was pointed out by Gilmore, the solution of Eq. (3.3) for b which will best fit the geometric configuration of the well functioning instruments is given by

$$\mathbf{b} = \left(\mathbf{H}^{\mathrm{T}} \lambda \mathbf{H}\right)^{-1} \mathbf{H}^{\mathrm{T}} \lambda \mathbf{m} \tag{3.7}$$

where $\lambda = \operatorname{diag}(\lambda_a, \lambda_b, \lambda_c, \lambda_d, \lambda_e, \lambda_f)$ is the "status" matrix, with $\lambda_1 = 1$ or 0 according to whether instrument i, i=a,b,c,d,e,f, is error free or not.

Of course, for this solution to be meaningful, at least three out of the six instruments has to be error free. There are 42 different combinations with at least three of the λ_1 being equal to 1. After having evaluated explicitly the matrix

$$\mathbf{H}^{\mathbf{I}} = \left(\mathbf{H}^{\mathbf{T}} \lambda \mathbf{H}\right)^{-1} \mathbf{H}^{\mathbf{T}} \lambda \tag{3.8}$$

for all the proper 42 combinations of the λ_i , it becomes evident that the total number of different nonzero entries of H* for the various combinations is only 25. In terms of S and C, these 25 entries are as shown in Table 3.1.

TABLE 3.1
Twenty Five Required Data-Word Matrix

$$\begin{split} N_1 &= \frac{1}{10} \Big(2S + C \Big) & N_{11} &= \frac{1}{4} \Big(S + 4C \Big) & N_{21} &= 2S + C \\ N_2 &= \frac{1}{10} \Big(7S + C \Big) & N_{12} &= \frac{1}{4} \Big(3S + C \Big) & N_{22} &= \frac{1}{2} \Big(3S - C \Big) \\ N_3 &= \frac{1}{5} \Big(S + 3C \Big) & N_{13} &= \frac{3}{4} S & N_{23} &= \frac{1}{2} \Big(S + 3C \Big) \\ N_4 &= \frac{1}{10} \Big(-S + 7C \Big) & N_{14} &= \frac{3}{4} C & N_{24} &= \frac{1}{4} \Big(S - C \Big) \\ N_5 &= \frac{1}{10} \Big(S - 2C \Big) & N_{15} &= \frac{1}{4} \Big(-S + 3C \Big) & N_{25} &= \frac{1}{4} \Big(S + C \Big) \\ N_6 &= \frac{1}{5} \Big(3S - C \Big) & N_{16} &= \frac{1}{4} \Big(2S - C \Big) & N_{17} &= \frac{1}{4} \Big(S + 2C \Big) \\ N_7 &= \frac{1}{10} \Big(2S - C \Big) & N_{17} &= \frac{1}{4} \Big(S + 2C \Big) \\ N_8 &= \frac{1}{2} S & N_{18} &= \frac{1}{2} \Big(-S + 2C \Big) \\ N_9 &= \frac{1}{2} C & N_{19} &= \frac{1}{2} \Big(2S + C \Big) \\ N_{10} &= \frac{1}{4} \Big(4S - C \Big) & N_{20} &= -S + 2C \end{split}$$

The 42 explicit evaluations of H^I are given in Table 3.2 in terms of the indices of the above listed N_i 's. For instance, the H^I matrix for the combination $\lambda_a = \lambda_b = \lambda_e = 1$ and $\lambda_c = \lambda_d = \lambda_f = 0$, which is given by

$$\mathbf{H}^{\mathbf{I}} = \begin{bmatrix} \mathbf{N}_{19} & -\mathbf{N}_{19} & 0 & 0 & 0 & 0 \\ -\mathbf{N}_{22} & -\mathbf{N}_{22} & 0 & 0 & \mathbf{N}_{20} & 0 \\ \mathbf{N}_{18} & \mathbf{N}_{18} & 0 & 0 & 0 & 0 \end{bmatrix} . \tag{3.9}$$

In Table 3.2 \sim 0 stands for the number zero and the numbers shown represent the N₁ terms by listing only the subscript number ($\pm i$), e.g., N₁₂=12. For the expression in Eq. (3.9), this yields

$$\lambda_{a}, \lambda_{b}, \lambda_{e} = 1 \qquad \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 \\ -22 & -22 & 0 & 0 & 20 & 0 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} . \tag{3.10}$$

3.1.2 <u>Implementation of Pseudo-Inverse and Status Matrices Method Using LSI Packaged Basic Elements</u>

The implementation of the transformation described in 3.1.1 essentially involves the use of a read-only memory and an arithmetic unit to provide the appropriate overflows to the 3-axis system's input buffer logic.

The following discussion will treat each section of the system in enough detail to make clear the functional interaction of the sections in achieving the required final results. There are four sections of the system: they are (1) the six input gyro-sync logic, (2) the read-only memory, (3) the arithmetic unit, and (4) the direction cosine computer's (SIMU) input buffer logic.

The gyro-sync logic performs two operations. First, the six $(\pm x, \pm y, \pm z)$ asynchronous gyro inputs are synchronized to computer word time. Second, these six signals are encoded so as to be sent out as three octal variables (see Fig. 3-1).

To understand the need for this memory configuration refer to Table 3.2, which shows the manner in which the basic constants shown in Table 3.1 are used. The entries in Table 3.1 are a summary of the various products of a constant times $\frac{1}{2}\sin\alpha$ and $\frac{1}{2}\cos\alpha$ as discussed in Sec. 3.1.1.

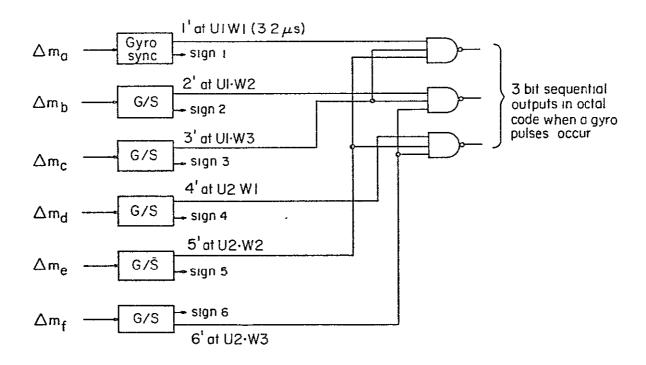


FIG. 3-1 Incremental input encoding for the six-gyro system.

TABLE 3.2 Status Matrices

$$\lambda_{\mathbf{g}}, \lambda_{\mathbf{b}}, \lambda_{\mathbf{c}} = 1 \quad \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 \\ -23 & 23 & 21 & 0 & 0 & 0 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \lambda_{\mathbf{a}}, \lambda_{\mathbf{e}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 21 & 0 & 0 & 0 & -23 & 23 \\ 0 & 0 & 0 & 0 & 18 & 18 \\ 0 & 0 & 0 & 0 & 19 & -19 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{b}}, \lambda_{\mathbf{d}} = 1 \quad \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 \\ 23 & -23 & 0 & -21 & 0 & 0 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \lambda_{\mathbf{b}}, \lambda_{\mathbf{c}}, \lambda_{\mathbf{d}} = 1 \quad \begin{bmatrix} 0 & 0 & 18 & 18 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 0 & 20 & 22 & 22 & 0 & 0 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{b}}, \lambda_{\mathbf{c}} = 1 \quad \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 & 0 \\ -22 & -22 & 0 & 0 & 20 & 0 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \lambda_{\mathbf{b}}, \lambda_{\mathbf{c}}, \lambda_{\mathbf{c}} = 1 \quad \begin{bmatrix} 0 & 18 & 23 & 0 & -19 & 0 \\ 0 & -19 & -18 & 0 & 23 & 0 \\ 0 & 23 & 19 & 0 & -18 & 0 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{b}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 & 0 \\ 22 & 22 & 0 & 0 & 0 & 20 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \lambda_{\mathbf{b}}, \lambda_{\mathbf{c}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 0 & -22 & 19 & 0 & 0 & -18 \\ 0 & 18 & 22 & 0 & 0 & 19 \\ 0 & 19 & 18 & 0 & 0 & -22 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{c}}, \lambda_{\mathbf{d}} = 1 \quad \begin{bmatrix} 0 & 0 & 18 & 18 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 0 & 0 & -22 & -22 & 0 & 0 \end{bmatrix} \quad \lambda_{\mathbf{b}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{e}} = 1 \quad \begin{bmatrix} 0 & -22 & 0 & 19 & 18 & 0 \\ 0 & -18 & 0 & -22 & 19 & 0 \\ 0 & 19 & 0 & 18 & 22 & 0 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{c}}, \lambda_{\mathbf{e}} = 1 \quad \begin{bmatrix} 22 & 0 & 19 & 0 & -18 & 0 \\ -18 & 0 & 22 & 0 & 19 & 0 \\ -19 & 0 & -18 & 0 & 0 & 23 \\ 23 & 0 & -19 & 0 & 0 & 18 \end{bmatrix} \quad \lambda_{\mathbf{b}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 0 & -21 & 0 & 0 & 23 & -23 \\ 0 & 0 & 0 & 0 & 18 & 18 \\ 0 & 0 & 0 & 0 & 0 & 19 & -19 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} -16 & 0 & 0 & 23 & 19 & 0 \\ -19 & 0 & 0 & 18 & 23 & 0 \\ 23 & 0 & 0 & -19 & -18 & 0 \end{bmatrix} \quad \lambda_{\mathbf{c}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 0 & 0 & 18 & 18 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 0 & 0 & 23 & 23 & 21 & 0 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 0 & 0 & 18 & 18 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 0 & 0 & 23 & -23 & 23 & 21 \end{bmatrix}$$

$$\lambda_{\mathbf{a}}, \lambda_{\mathbf{d}}, \lambda_{\mathbf{f}} = 1 \quad \begin{bmatrix} 0 & 0 & 18 & 18 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 0 & 0 & 23 & 23 & 23 & 0 \end{bmatrix}$$

TABLE 3.2 Status Matrices (cont.)

$$\begin{array}{c} \lambda_{\mathbf{c}},\lambda_{\mathbf{c}},\lambda_{\mathbf{f}}=1 & \begin{bmatrix} 0 & 0 & 20 & 0 & -22 & -22 \\ 0 & 0 & 0 & 0 & 118 & 18 \\ 0 & 0 & 0 & 0 & 19 & -19 \end{bmatrix} & \lambda_{\mathbf{d}},\lambda_{\mathbf{c}}=0 & \begin{bmatrix} 13 & -12 & 17 & 0 & 0 & -25 \\ 16 & 17 & 10 & 0 & 0 & 11 \\ 15 & 14 & -24 & 0 & 0 & -16 \end{bmatrix} \\ \lambda_{\mathbf{d}},\lambda_{\mathbf{e}},\lambda_{\mathbf{f}}=1 & \begin{bmatrix} 0 & 0 & 0 & 20 & 22 & 22 \\ 0 & 0 & 0 & 0 & 18 & 18 \\ 0 & 0 & 0 & 0 & 19 & -19 \end{bmatrix} & \lambda_{\mathbf{c}},\lambda_{\mathbf{e}}=0 & \begin{bmatrix} 12 & -13 & 0 & 17 & 0 & 25 \\ 17 & 16 & 0 & -10 & 0 & 11 \\ 14 & 15 & 0 & 24 & 0 & -16 \end{bmatrix} \\ \lambda_{\mathbf{e}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 8 & -8 & 9 & 0 & 0 & 0 \\ 0 & 0 & 19 & -19 & 0 & 0 \\ 18 & 18 & 0 & 0 & 0 & 0 \end{bmatrix} & \lambda_{\mathbf{b}},\lambda_{\mathbf{e}}=0 & \begin{bmatrix} 16 & 0 & 15 & 14 & 0 & -24 \\ 25 & 0 & 13 & -12 & 0 & 17 \\ 11 & 0 & -16 & -17 & 0 & -10 \end{bmatrix} \\ \lambda_{\mathbf{e}},\lambda_{\mathbf{d}}=0 & \begin{bmatrix} 19 & -19 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 18 & 18 \\ 9 & 9 & 0 & 0 & 8 & -8 \end{bmatrix} & \lambda_{\mathbf{a}},\lambda_{\mathbf{e}}=0 & \begin{bmatrix} 0 & -16 & 14 & 15 & 0 & 24 \\ 0 & 25 & 12 & -13 & 0 & 17 \\ 0 & 11 & 17 & 16 & 0 & -10 \end{bmatrix} \\ \lambda_{\mathbf{d}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 12 & -13 & 17 & 0 & -25 & 0 \\ -17 & -16 & 10 & 0 & 11 & 0 \\ 14 & 15 & 24 & 0 & 16 & 0 \end{bmatrix} & \lambda_{\mathbf{b}},\lambda_{\mathbf{d}}=0 & \begin{bmatrix} 10 & 0 & 11 & 0 & -16 & -17 \\ 24 & 0 & 16 & 0 & 14 & 15 \\ 17 & 0 & -25 & 0 & 12 & -13 \end{bmatrix} \\ \lambda_{\mathbf{c}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 13 & -12 & 0 & 17 & 25 & 0 \\ -16 & -17 & 0 & -10 & 11 & 0 \\ 15 & 14 & 0 & -24 & 16 & 0 \end{bmatrix} & \lambda_{\mathbf{b}},\lambda_{\mathbf{c}}=0 & \begin{bmatrix} 19 & 0 & 0 & 11 & 16 & 17 \\ -24 & 0 & 0 & -16 & 15 & 14 \\ 0 & 17 & 25 & 0 & 13 & -12 \end{bmatrix} \\ \lambda_{\mathbf{b}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 16 & 0 & 14 & 15 & 24 & 0 \\ -25 & 0 & 12 & -13 & 17 & 0 \\ -15 & 0 & -25 & 13 & -12 & 17 & 0 \\ 11 & 0 & -17 & -16 & 10 & 0 \end{bmatrix} & \lambda_{\mathbf{f}},\lambda_{\mathbf{c}}=0 & \begin{bmatrix} 0 & -10 & 0 & 11 & 17 & 16 \\ 0 & 24 & 0 & -16 & 14 & 15 \\ 0 & 17 & 0 & 25 & 12 & -13 \end{bmatrix} \\ \lambda_{\mathbf{g}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 16 & 0 & 14 & 15 & 24 & 0 \\ -25 & 0 & 12 & -13 & 17 & 0 \\ 11 & 0 & -17 & -16 & 10 & 0 \end{bmatrix} & \lambda_{\mathbf{f}},\alpha_{\mathbf{c}}=0 & \begin{bmatrix} 8 & -8 & 9 & 9 & 0 & 0 \\ -1 & -1 & 2 & -2 & 3 & 0 \\ -1 & -1 & 2 & -2 & 3 & 0 \\ 4 & 5 & -5 & 6 & 0 \end{bmatrix} \\ \lambda_{\mathbf{g}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 8 & -8 & 9 & 9 & 0 & 0 \\ -1 & -1 & 2 & 2 & -2 & 3 & 0 \\ -1 & 4 & 5 & 5 & 6 & 0 \end{bmatrix} \\ \lambda_{\mathbf{g}},\lambda_{\mathbf{f}}=0 & \begin{bmatrix} 8 & -8 & 9 & 9 & 0 & 0 \\ -1 & -1 & 2 & 2 & -3 & 5 & 6$$

TABLE 3.2 Status Matrices (cont.)

$$\lambda_{e} = 0 \qquad \begin{bmatrix} 8 & -8 & 9 & 9 & 0 & 0 \\ 1 & 1 & 2 & -2 & 0 & 3 \\ 4 & 4 & -5 & 5 & 0 & -6 \end{bmatrix} \qquad \lambda_{b} = 0 \qquad \begin{bmatrix} 6 & 0 & 4 & 4 & 5 & -5 \\ 0 & 0 & 8 & -8 & 9 & 9 \\ 3 & 0 & -1 & -1 & 2 & -2 \end{bmatrix}$$

$$\lambda_{d} = 0 \qquad \begin{bmatrix} 2 & -2 & 3 & 0 & -7 & -7 \\ 5 & -5 & 6 & 0 & 4 & 4 \\ 9 & 9 & 0 & 0 & 8 & -8 \end{bmatrix} \qquad \lambda_{a} = 0 \qquad \begin{bmatrix} 0 & -6 & 4 & 4 & -5 & 5 \\ 0 & 0 & 8 & -8 & 9 & 9 \\ 0 & 3 & 1 & 1 & 2 & -2 \end{bmatrix}$$

$$\lambda_{c} = 0 \qquad \begin{bmatrix} 2 & -2 & 0 & 3 & 7 & 7 \\ -5 & 5 & 0 & -6 & 4 & 4 \\ 9 & 9 & 0 & 0 & 8 & -8 \end{bmatrix} \qquad \lambda_{a}, \lambda_{b}, \lambda_{c}, \lambda_{d}, \lambda_{e}, \lambda_{f} = 1 \qquad \begin{bmatrix} 8 & -8 & 9 & 9 & 0 & 0 \\ 0 & 0 & 8 & -8 & 9 & 9 \\ 9 & 9 & 0 & 0 & 8 & -8 \end{bmatrix}$$

In operation, the first read-only memory determines which matrix in Table 3 2 will be required to process the sensors which are operable ($\lambda_1^{=1}$). The second memory selects the words specified by this matrix. These words are stored as in Table 3.1. They are processed with the appropriate timing to allow each of the triad axes to be updated for any gyro outputs that have occurred. These words are used in 42 different sequences in performing the transformations in the arithmetic unit. There are three sets of memories as described above for processing from six to three axes, one for each of the triad axes.

The arithmetic unit consists of an adder and five data registers used in parallel processing to transform to $\Delta\theta x$, $\Delta\theta y$ and $\Delta\theta z$ (see Fig. 3-2). The sequence of events is as follows. Starting the updating to obtain a $\Delta\theta x$ input to the computer, the first specified word from the second read-only memory (ROM) (of the set of six words specified by the first ROM for the x-axis update) is loaded into the constant buffer. From the buffer the scaled increment is added to the previous remainder of $\Delta\theta x$ and the result is held in the general $\Delta\theta$ buffer register. Once this is done the selection of the next constant for the x-axis update from the ROM can begin. The $\Delta\theta x$ register is loaded again to prepare for the next component of the $\Delta\theta x$ update. After the six cycles are completed the remainder will be in the $\Delta\theta x$ remainder register and an output will be sent to the gyro-buffer logic if the entire update produced either a positive or negative overflow.

The gyro-buffer will recognize this overflow as the signal to produce a positive or negative output pulse that will update the appropriate direction cosines. This sequence will be followed by the second set of ROM's and its arithmetic register to provide a $\Delta\theta y$ input to the direction cosine matrix, if the inputs are of sufficient magnitude to produce an overflow. The same sequence will take place for the final set of ROM's to produce a $\Delta\theta z$ input pulse when required.

The above constitutes a complete update cycle and takes place within the system update time of 57.6 µs. The computer described above can function continuously at any input rate desired that does not exceed this pulse repetition rate.

3.2 CONVERSION FROM DODECAHEDRON TO TRIAD BY SENSOR CORRECTION

3.2.1 Description

In this section a method for converting sensor signals from redundant dodecahedron to equivalent triad axes is described in which signals missing because of sensor failure are restored by synthesis from operational sensor outputs. The resulting six inertial signals are then used as the input to a fixed transformation whose output is the desired equivalent triad set. A block diagram of the system is shown in Fig. 3-3. It consists of a sensor failure detection unit, a correction unit, and a dodecahedron-to-triad conversion unit. The detection unit is the parity equation integrator, which will be described in Sec. 3.2.2. The detection unit produces as its output a six-element binary vector, λ , each of whose elements, when equal to unity, affirms the operation of one of the sensors. The λ vector and the sensor outputs serve as inputs to the sensor correction unit. If a particular sensor is operative, the output of the correction unit corresponding to that sensor is the sensor signal itself. If a sensor has failed, then the correction unit output corresponding to that sensor is an estimate of what the sensor signal should be, derived from the operative sensor signals It is clear that at least three sensors must be operative in order that such an estimate can be made.

The six sensor signals (synthetic or actual) from the correction unit are used as inputs to the dodecahedron-to-triad conversion unit. Since six sensor signals are always assumed to be present at the input of this unit, even when as many as three sensors have actually failed, a simple, fixed conversion algorithm may be used. The techniques employed and the system itself will now be described in greater detail.

The method used for synthesizing failed-sensor signals is based upon solution of one of the parity equations for the missing signal in terms of the three valid signals. The parity equations, as defined by Gilmore, are reproduced here as Table 3.3. As an example, if sensor A has failed but sensors B, C, and D are still operating, then Eq. (1) in Table 3.3 may be used for estimating A, viz,

$$A = B + \gamma(C + D)$$
 (3.11)

where

$$\gamma = \frac{\sin(\alpha)}{\cos(\alpha)} = \frac{\sqrt{5} - 1}{2} = 0.618033 \quad . \tag{3.12}$$

A is the estimate of the output that would be obtained from sensor A if it were operating and α is the angle between two intersecting normals to adjacent faces of a dodecahedron. A general equation may be written for sensor correction:

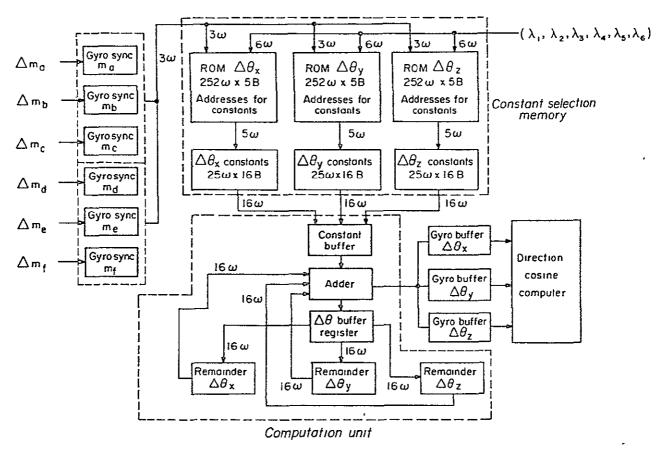


FIG. 3-2 Block diagram of six-gyro system using pseudo-inverse and status matrices method.

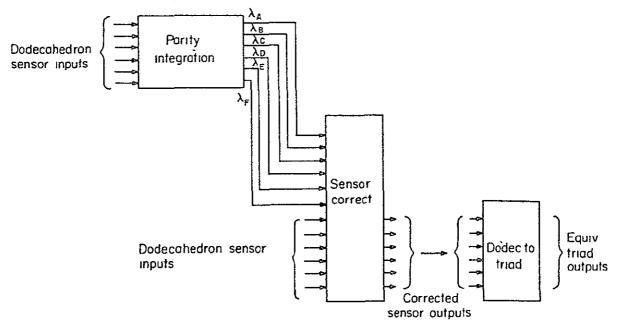


FIG. 3-3 Block diagram of sensor correction method.

$$\hat{1} = \lambda_{1} 1 + \overline{\lambda}_{1} \left\{ \left(\lambda_{2} \lambda_{3} \lambda_{4} \overline{\lambda}_{6} + \lambda_{2} \lambda_{3} \lambda_{4} \lambda_{5} \right) E_{A} \right.$$

$$+ \lambda_{2} \lambda_{3} \overline{\lambda}_{4} \lambda_{5} \overline{\lambda}_{6} E_{B} + \lambda_{2} \lambda_{3} \overline{\lambda}_{5} \lambda_{6} E_{C}$$

$$+ \lambda_{2} \overline{\lambda}_{3} \lambda_{4} \lambda_{5} E_{D} + \lambda_{2} \overline{\lambda}_{3} \lambda_{4} \overline{\lambda}_{5} \lambda_{6} E_{C}$$

$$+ \lambda_{2} \overline{\lambda}_{3} \overline{\lambda}_{4} \lambda_{5} \lambda_{6} E_{F} + \overline{\lambda}_{2} \lambda_{3} \lambda_{4} \lambda_{5} \overline{\lambda}_{6} E_{G}$$

$$+ \lambda_{2} \overline{\lambda}_{3} \overline{\lambda}_{4} \lambda_{5} \lambda_{6} E_{F} + \overline{\lambda}_{2} \lambda_{3} \lambda_{4} \lambda_{5} \overline{\lambda}_{6} E_{G}$$

$$+ \overline{\lambda}_{2} \lambda_{3} \lambda_{4} \overline{\lambda}_{5} \lambda_{6} E_{4} + \lambda_{3} \overline{\lambda}_{4} \lambda_{5} \lambda_{6} E_{I}$$

$$+ \overline{\lambda}_{2} \lambda_{4} \lambda_{5} \lambda_{6} E_{J} \right\} \qquad (3.13)$$

TABLE 3.3 Failure Detection Parity Equations

No.	Instrument	Equation									
1	ABCD	(A - B)c - (C + D)s = 0									
2	ABCE	(B + C)c - (A + E)s = 0									
3	ABCF	(C - A)c + (B - F)s = 0									
4	ABDE	(D - A)c + (B + E)s = 0									
5	ABDF	(B + D)c - (A - F)s = 0									
6	ABEF	(E - F)c - (A + B)s = 0									
7	ACDE	(D + E)c - (A - C)s = 0									
8	ACDF	(F - C)c + (A + D)s = 0									
9	ACEF	(A + F)c - (C + E)s = 0									
10	ADEF	(E - A)c + (D - F)s = 0									
11	BCDE	(E - C)c + (D - B)s = 0									
12	BCDF	(F + D)c + (B - C)s = 0									
13	BCEF	(B - E)c + (C + F)s = 0									
14	BDEF	(B + F)c + (D - E)s = 0									
15	CDEF	(C - D)c - (E + F)s = 0									
	$c = \cos(\alpha) = \left(\frac{\sqrt{5} + 5}{10}\right)^{\frac{1}{2}} \approx 0.85065$ $s = \sin(\alpha) = \left(\frac{5 - \sqrt{5}}{10}\right)^{\frac{1}{2}} \approx 0.52574$										

To interpret Eq. (3.13) let 1 represent the output of sensor 1 and let $\hat{1}$ represent the estimate of this quantity. The various λ 's are the operational indicators of their respective sensors or, when barred, the complements of these quantities. Finally, the quantities E_A , E_B , etc., represent the parity equations to be used in computing $\hat{1}$. Thus, Eq. (3.13) serves to select which (if any) equation will be used to synthesize the sensor output, based upon the operational status of all sensors in the system.

Equation (3.13) can be made specific to any particular sensor by means of Table 3.4, which indicates the substitution of subscripts for correction of a given sensor. The synthesis of a failed-sensor output from one of the parity equations involves multiplying certain of the operational outputs by either unity, γ or $\gamma^{-1} = 1 + \gamma$ and then summing these quantities. The selection of quantities to be summed to produce the desired synthetic sensor output is governed by the λ vector. A resolver implementation of sensor output synthesis is shown in Fig 3-4 for the general case. Six such resolvers are required, one for each dodecahedron axis. The resolver signals $S_{_{1}}$, either multiplied by γ or by unity, are gated into a resolver by sequencing signals T_{ij} and control signals C_{ij} . The overflow output of this resolver is the dodecahedron sensor signal, either synthetic or real, to be used in the dodecahedron-totriad conversion. The control signals C_{ij} are derived from Eq. (3.13) as functions of the λ vector and are given in general form by Table 3.5. Table 3.5 is made specific to a particular sensor by means of Table 3.4. Implementation of the control functions is by means of a read-only memory whose inputs are the five λ_i and whose outputs are the C_{ij} . This memory has a capacity of 16 words, each 15 bits long. Six identical memories are used, one for each of the dodecahedron sensors. Each memory is made specific to an axis by the combination and permutation of λ 's used as its input. These are specified by Table 3.4.

TABLE 3.4

Table for Substitution in General 1-Gyro Restoring Equation

	General Variable															
Sensor	λ ₁	λ2	λ_3	λ ₄	λ ₅	λ ₆	EA	EB	EC	E_{D}	$\mathbf{E}_{\mathbf{E}}$	$^{\rm E}_{ m F}$	$^{\rm E}_{\rm G}$	$\mathbf{E}_{\mathbf{H}}$	$\mathbf{E}_{\mathbf{I}}$	$^{\rm E}_{ m J}$
А	λ _A	λ _B	^λ с	λ _D	λ _E	λ _F	E ₁	E ₂	E ₃	E ₄	E ₅	E ₆	E ₇	E ₈	E ₉	E ₁₀
В	λ _B	$^{\lambda}_{A}$	$^{\lambda}$ C	${}^\lambda \!\!\!\!D$	$^{\lambda}_{F}$	$^{\lambda}E$	El	E ₃	E_2	E ₅	E ₄	Е ₆	E ₁₂	E ₁₁	E ₁₃	E ₁₄
C	'nс	_D	$^{\lambda}_{\text{E}}$	$^{\lambda}_{F}$	$^{\lambda}A$	${}^{\lambda}_{\mathbf{B}}$	E ₁₅	E ₇	E ₁₁	E_8	E ₁₂	$\mathbf{E_1}$	E ₉	E ₁₃	E2	E_3
Ď	λ _D	$^{\lambda}c$	$\boldsymbol{\lambda}_{E}$	$^{\lambda}\mathbf{F}$	$^{\lambda}_{\mathrm{B}}$	_A	E ₁₅	E ₁₁	E ₇	E ₁₂	E ₈	$^{\mathtt{E}}_{1}$	E ₁₄	E ₁₀	E4	E ₅
E	λ _E	${}^\lambda F$	${}^\lambda\!A$	${}^\lambda \! _B$	$^{\lambda}c$	$\boldsymbol{\lambda}_{D}$	E ₆	E ₉	E ₁₀	E ₁₃	E ₁₄	E ₁₅	E ₂	E ₄	E ₇	E ₁₃
F	λ _F	${}^{\lambda}E$	_A	$^{\lambda}B$	${}^\lambda D$	$^{\lambda}$ C	E ₆	E ₁₀	E ₉	E ₁₄	E ₁₃	E ₁₅	^E 5	E ₃	E ₈	E ₁₂

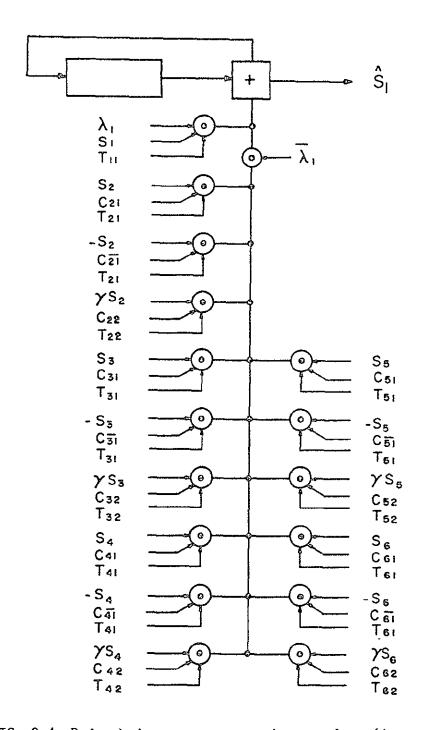


FIG. 3-4 Dodecahedron gyro correction resolver (6 required).

TABLE 3.5
Table of Binary Constants for Dodecahedron Gyro Correction (see Fig. 3-4)

Eq.	λ ₂	^λ 3	λ4	λ ₅	λ ₆	c ₂₁	c ₂₁	c ₂₂	c ₃₁	c <u>31</u>	c ₃₂	c ₄₁	c ₄₁	c ₄₂	c ₅₁	c <u>51</u>	c ₅₂	c ₆₁	c_61	c ₆₂
A	1	1	1	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0
	1	1	1	1	0															
	1	1	1	1	1												·			
В	1	1	0	1	0	1	0	1	1	0	1	0	0	0	0	1	0	0	0	0
С	1	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1
	1	1	1	0	1							_								
D	1	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0
<u> </u>	1	0	l	1	1															
E	1	0	1	0	1	1	0	1	0_	0	0	1	0	1	0	0	0	1	0	0
F	1	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	1
G	0	1	1	1	0	0	0	0	1	0	0	1	0	1	1	0	1	0	0	0
Н	0	1	1	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1
I	0	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0
	1	`1	0	1	1															
J	0	0	1	1	1	0	0	0	0	0	0	0	0,	1	1	0	0	0	0	1
	0	1	1	1	1															

When all six dodecahedron sensor signals are assumed present, the dodecahedron-to-triad conversion takes the form

$$\begin{bmatrix}
S_{\mathbf{X}} \\
S_{\mathbf{y}} \\
S_{\mathbf{Z}}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
\sin \alpha & -\sin \alpha & \cos \alpha & \cos \alpha & 0 & 0 \\
0 & 0 & \sin \alpha & -\sin \alpha & \cos \alpha & \cos \alpha \\
\cos \alpha & \cos \alpha & 0 & 0 & \sin \alpha & -\sin \alpha
\end{bmatrix} \cdot \begin{bmatrix} \hat{\mathbf{S}}_{\mathbf{A}} \\ \hat{\mathbf{S}}_{\mathbf{B}} \\ \hat{\mathbf{S}}_{\mathbf{C}} \\ \hat{\mathbf{S}}_{\mathbf{D}} \\ \hat{\mathbf{S}}_{\mathbf{E}} \\ \hat{\mathbf{S}}_{\mathbf{F}}
\end{bmatrix} (3.14)$$

The implementation of the conversion is by means of three resolver circuits, each identical to the one shown in Fig. 3-5. Whole-number representations of the constant half-sines and half-cosines are gated into the resolver by synthetic sensor outputs \hat{S}_i , in accordance with Eq. (3.14) and by sequencing signals T_i . The overflow output of each resolver is the respective triad signal.

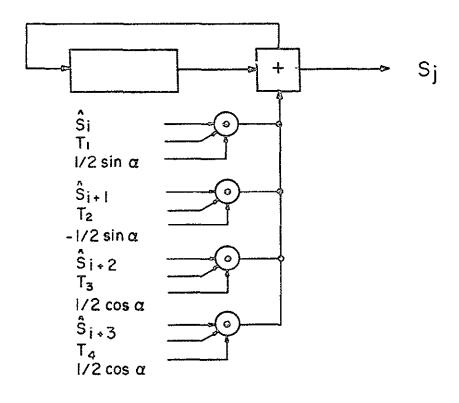


FIG. 3-5 Triad axis generator (3 required).

3.2.2 Parity Integration

To implement the parity equation determination of gyro failure, a weighted integration technique will be adopted. The reasoning behind the use of integration is that quantization effects in both the gyros and the computer must be separated from significant gyro deviations. Weighting is included to mask out long-term drift due to roundoff and other effects within the parity computation itself. Consistent with other sections of the computer, an operational digital procedure will be used in the parity section of the system.

The form of the parity conditions used closely resembles that shown by Gilmore. That is, for the first parity equation

$$Q_1 = (S_A - S_B)\cos \alpha - (S_C + S_D)\sin \alpha \qquad (3.15)$$

where S_1 is the output of gyro i and is a measure of w_1 . For perfect gyros, $Q_1=0$. Thus Q_1 represents an angular-rate error. Since pulsed gyros are assumed, where each output pulse represents an increment of angle, the first parity equation may be written in angle form as

$$dX_{1} = Q_{1}dt = \left(d\theta_{A} - d\hat{\theta}_{B}\right)\cos\alpha - \left(d\theta_{C} + d\theta_{D}\right)\sin\alpha \qquad (3.16)$$

and similarly for the other equation. Temporal weighting and integration are introduced by defining the quantity $P_{_{\mathbf{1}}}$,

$$P_{1} = \int_{0}^{t} e^{-K(t-\tau)} dX_{1}$$
 (3.17)

or

$$P_{1} = \int_{0}^{t} e^{-K(t-\tau)} \left(\frac{dX_{1}(\tau)}{d\tau}\right) d\tau \qquad (3.18)$$

If $dX_1/dt = 0$ for t < 0 then P_1 is seen to be the convolution of dX_1/dt with e^{-Kt} The differential form of the above integral equation may readily be shown to be

$$\frac{dP_1}{dt} = -KP_1 + \frac{dX_1}{dt}$$
 (3.19)

or

$$dP_{1} = -KP_{1}dt + dX_{1}$$
 (3.20)

The final form implies a simple DDA solution, as shown in Fig. 3-6.

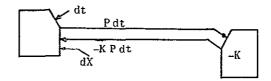


FIG. 3-6 DDA solution.

The implementation of this configuration using resolvers is shown in Fig. 3-7. A complete solution to allow correction of two failures and detection of three simultaneously requires 15 units of the type in Fig. 3-7, although the elements so designated may be shared among the 15 systems. It is also possible to mechanize a single-failure correction scheme using just six of the units in Fig. 3-7 in which the dX₁ inputs are switched among the parity networks. The gyro failures (up to two) are indicated by the binary quantities λ_1 , i=A,B,C,D,E,F. The value λ_1 =1 corresponds to the condition that gyro i is operative. The λ_1 are binary functions of the parity threshold functions E_1 . Specifically,

$$\overline{\lambda}_{1} = \prod_{\substack{\text{subset} \\ i}} \left(E_{j} \right)$$
 (3.21)

The E subset for each λ is indicated by Table 3.6. The E numbering corresponds to Table 2 in Gilmore. Detection of three or more failures is given by

$$\overline{\lambda}_{\mathbf{T}} = \prod_{j=1}^{15} \mathbf{E}_{\mathbf{J}} \quad . \tag{3.22}$$

The condition $\lambda_T = O(\overline{\lambda}_T = 1)$ indicates that at least three gyros have failed, but the failures cannot be isolated. This is equivalent to complete system failure.

The rationale behind the use of the weighted integral form of parity equation follows that discussed by Keene.² The prevalent type of sensor failure is performance degradation, evidenced by either scale factor change or by excessive bias. Let g be the sensor output. Then

$$a = (a + \varepsilon)w + b \tag{3.23}$$

where a is the scale factor, & is the scale factor error, b is the bias, and w is the measured quantity. Since integrating sensors are normally used, the output of interest is

$$\int gdt = (a + \epsilon) \int udt + bt . \qquad (3.24)$$

Then for constant $\omega = \omega_0$

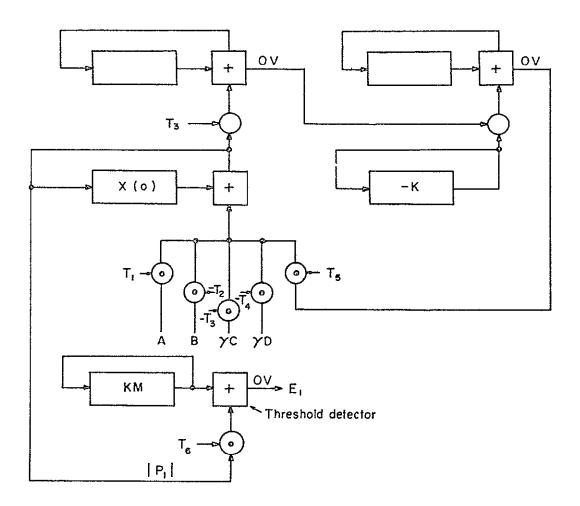


FIG. 3-7 Parity integrator.

TABLE 3.6 E Subset for λ_{i}

	$\frac{\lambda_{A}}{1}$	λ _B	$\frac{\lambda_{\mathbf{C}}}{\mathbf{C}}$	$\frac{\lambda_{D}}{\Delta}$	λ _E	λ _F
E	1	1	1	1		
E ₂	1	1	1		1	
E3	1	1	1			1
E4	1	1		1	1	
E ₅	1	1		1		1
E ₆	ι	1		•	1	1
E ₇	1		1	1	1	
E8	1		1	1		1
E ₉	1		1		1	1
E ₁₀	1			1	1	1
E ₁₁		1	1	1	1.	
E ₁₂		1	1	1	•	
E ₁ E ₂ E ₃ E ₄ E ₅ E ₆ E ₇ E ₈ E ₁₀ E ₁₁ E ₁₂ E ₁₃ E ₁₄ E ₁₅		1	1		1	1
E ₁₄		1		1	1	1
E ₁₅			1	1	1	1

$$\hat{\theta} = \int g dt = av_0 t + (\epsilon w_0 + b)t$$
 (3.25)

implying a ramp error behavior. Since X_i is a linear combination of the $\hat{\theta}$'s, it too exhibits ramp behavior under these conditions. Let $X_i = \theta_0 t$. Then Eq. (3.19) becomes

$$\frac{dP_1}{dt} = -KP_1 + Q_0 {(3.26)}$$

or

$$P_1 = \frac{Q_0}{K} \left(1 - e^{-Kt} \right)$$
 (3.27)

If $\, \, \text{M} \,$ is defined as the maximum allowable value of $\, \, \text{P}_{1} \,$, then threshold is exceeded for

$$\frac{Q_0}{K} \left(1 - e^{-Kt} \right) > M$$
 (3.28)

Solving for the time \mathbf{t}_{M} at which the inequality is satisfied,

$$t_{M} > \frac{1}{K} \ell_{n} \left(\frac{Q_{o}}{Q_{o} - KM} \right)$$
 (3.29)

Thus, KM is established as the minimum error rate for parity failure, and the time until such failure is detected is adjusted by K and decreases with increasing Q_{0} .

3.2.3 Constant Rate Multipliers

Although it has been suggested that standard resolvers be used to effect the multiplication of a sensor or other pulse-rate signal by a constant quantity, another interesting approach has been developed. The basis for this approach is given in Appendix A (Smooth Sequences) and stems from the realization that the pulse rate resulting from the multiplication of the source rate by a fixed quantity (less than unity) should preserve as well as possible the relative pulse density of the source. Although the use of resolver-type rate multipliers does in fact preserve relative densities optimally, several techniques have been developed which perform the same function with appreciable circuit savings. One of these well suited for applications in the dodecahedron sensor transformation computer will be described. Consider Fig. 3-8, which shows an interconnection of pulse counters and inhibit elements. The upper counter produces one output pulse for every all input pulses, and so forth. Each time a pulse counter produces an output pulse it inhibits one input pulse to the counter immediately above it. Analysis of this circuit shows that the pulse output frequency is equal to the pulse output frequency multiplied by P/Q, where P and Q are relatively prime integers and

Q are relatively prime integers and
$$\frac{P}{Q} = \frac{1}{a_1 + \frac{1}{a_2 + \frac{1}{a_3 + \frac{1}{a_4 + \dots}}}}$$
(3.30)

Equivalently, P output pulses are produced for every Q input pulses. The P output pulses so produced are synchronous with input pulses, but are spaced as uniformly over the input pulses as is possible.

The representation of P/Q in Eq. (3.30) is as a simple continued fraction. The properties of such fractions are well known. One property of particular interest here is the

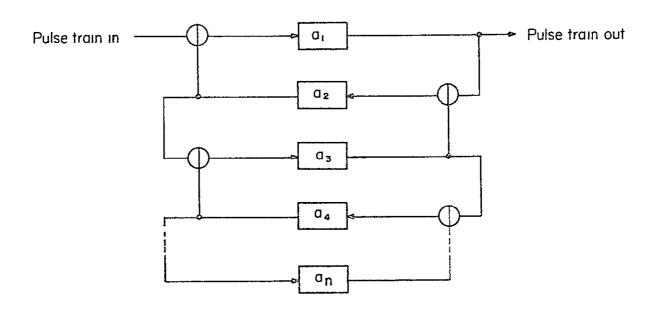


FIG. 3-8 Pulse rate multiplier.

representation of irrational numbers by their approximation in continued fraction form. Theory shows that all algebraic irrational numbers may be represented by an infinite continued fraction whose partial quotients (a in Eq. (3.30)) are bounded. The theory shows further that the approximation of any rational or irrational number by a truncated simple continued fraction is optimal in the sense that the absolute error incurred is smallest over all rational approximations with denominator no larger than that of the continued-fraction-derived approximation.

A case of special interest in the dodecahedron-to-triad conversion system is the multiplication of sensor output pulse rates by the quantities

$$\gamma = \frac{\sin \alpha}{\cos \alpha} = \frac{\sqrt{5} - 1}{2} \tag{3.31}$$

and

$$\gamma^{-1} = \frac{\cos \alpha}{\sin \alpha} = \frac{\sqrt{5+1}}{2} = 1 + \gamma$$
 (3.32)

where 2^{α} is the angle measured between any two dodecahedron normals. The expansion of γ as an infinite simple continued fraction is given in Eq. (3.33)

$$Y = \frac{1}{1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{1 + \cdots}}}}$$
 (3.33)

This leads to a very simple pulse-rate multiplier of the type shown in Fig. 3-8, since all the a_1 are unity and are therefore just direct connections. The resolution of this multiplier is determined by the number of stages used. For a resolver-type multiplier the resolution is doubled with each stage that is added to the storage register, since this has the effect of adding one more bit to the number added. It is interesting to compare the resolution per stage of the resolver to that of the continued fraction multiplier. Clearly, the resolution of an n-bit resolver-type multiplier is $1/2^n$ and is independent of the quantity by which the rate is multiplied. The approximate resolution of the continued fraction multiplier can be calculated using known properties of continued fraction expansions. The n^{th} convergent of a continued fraction is defined as the rational fraction obtained by truncating the continued fraction after the n^{th} partial quotient. If C_n is the n^{th} convergent of some continued fraction, then

$$C_n = P_n/Q_n \tag{3.34}$$

and

$$C_n - C_{n-1} = \frac{(-1)^{n-1}}{Q_n Q_{n-1}}$$
 (3.35)

In Eq. (3.33)

$$\lim_{n\to\infty} C_n = \gamma .$$

The odd-order convergents form a monotonic sequence that converges to γ from above and the even-order convergents form a monotonic sequence that converges to γ from below. The absolute error $E_n = |C_n - \gamma|$ is therefore bounded by the difference between the n^{th} and $n-1^{st}$ convergents. Letting this difference be D_n ,

$$|D_n| = |C_n - C_{n-1}| = \frac{1}{Q_n Q_{n-1}}$$
 (3.36)

and

$$|D_{n-1}| = |C_{n-1} - C_{n-2}| = \frac{1}{Q_{n-1}Q_{n-2}}$$
 (3.37)

but

$$\lim_{n\to\infty} Q_{n-1} = \gamma Q_n \qquad . \tag{3.37}$$

Therefore, in the limit,

$$D_n \to Y^2 D_{n-1}$$
 (3.38)

Thus, each additional partial quotient included in the continued fraction approximation to γ increases the resolution by a factor of approximately $\gamma^{-2}=(3+\sqrt{5})/2=2.618$, and as n increases the resolution approaches $1/\gamma^{-2n}=1/(1+\gamma)^{2n}$. The resolution of resolver-type and continued-fraction rate multipliers is compared in Table 3.7. In the strapdown system a resolution equivalent to a word length of 16 bits is generally required. It may be seen from Table 3.7 that this resolution is obtained using only twelve stages of the continued fraction multiplier. Another advantage of the continued fraction multiplier is that it is essentially a parallel system with no carry propagation delays. Therefore, slower electronic components may be used to attain the samespeeds as the equivalent resolver.

A working model of a 12-stage continued fraction multiplier was constructed. The circuit diagram of this unit appears as Fig. 3-9.

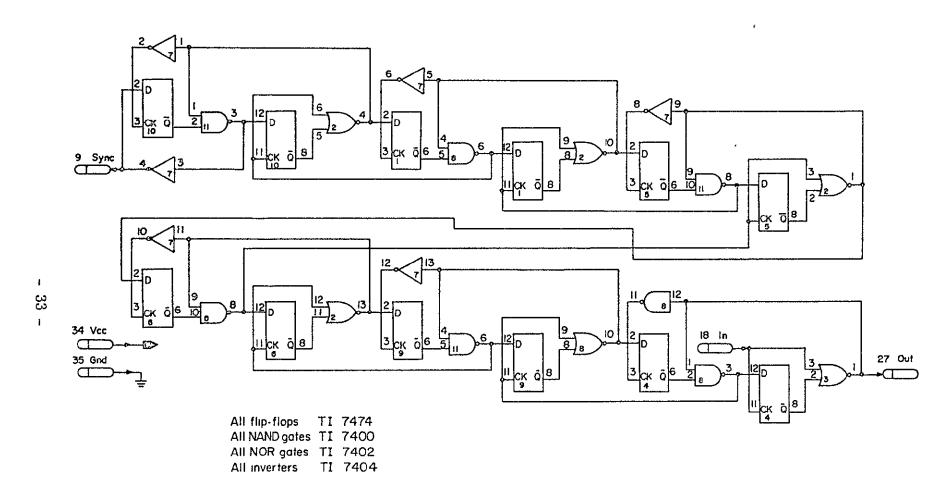


FIG. 3-9 Continued-fraction pulse rate multiplier.

TABLE 3.7

Comparison of Resolution of Resolver and Continued Fraction Ratio Multipliers

Posolution	Cont. Fraction Resolution
Keso fuctor	resolution
2	2
4	6
8	15
16	40
32	104
64	273
128	714
256	1870
512	4895
1024	12816
2048	33552
4096	87841
8192	229970
16384	602070
32768	1576239
65536	4126648
131072	10803704
	4 8 16 32 64 128 256 512 1024 2048 4096 8192 16384 32768 65536

REFERENCES

- "A Non-Orthogonal Multi-Sensor Strapdown Inertial Reference Unit," J. P. Gilmore, MIT/IL No. E2308, August 1968.
- 2. "The Meaning of Parity," D. Keene, MIT/IL, SIRU Memo No. 276, 28 Nov. 1969.

CHAPTER 4

INCREMENTAL COMPUTER CONFIGURATION FOR A REDUNDANT CMG CONTROL SYSTEM

4-1 INTRODUCTION

The objective of this study is to present an incremental computer structure for a space vehicle attitude control system that uses a set of six skewed, single-gimbal, control moment gyros (CMG's) as actuators and a set of six rate gyros in a dodecahedron configuration as rate sensors. The computer is to employ the redundancy in both the sensors and actuators to provide fail-operational performance. The CMG configuration of six skewed, single-gimbal gyros (exemplified by the Sperry 6-GAMS configuration) can be sized to provide three-axis control with failures in as many as three of its gyros, and the dodecahedron-configured rate gyro package can provide vehicle rate information from any three of its six rate gyros.

4.2 GENERAL DESCRIPTION OF THE CMG CONTROL SYSTEM

Since the computations to be performed by the CMG control computer are directly related to the specific configuration and steering law selected for the CMG's and also to the rate sensor configuration, these items are described briefly in paragraphs 4.2.1, 4.2.2, and 4.2.3, respectively. Paragraph 4.2.4 identifies the functions to be performed by the computer, including a discussion on three-variable versus six-variable input data to the steering law computer. A brief discussion on computer failure detection is presented in paragraph 4.2.5.

4.2.1 The CMG Configuration

Previous studies conducted jointly by Sperry and Lockheed for the Air Force' have identified a family of skewed, single-gimbal CMG configurations, denoted as the GAMS family of CMG configurations, to be the most efficient in terms of weight, power, and volume in providing redundant three-axis attitude control. Specifically, the 6-GAMS configuration, illustrated in Figure 4.2-1, is particularly suitable where control is to be maintained with any two of the six CMG's not operating. Although the control computer in this study is directed principally toward this configuration, the results are expected to be adaptable to other configurations.

The black arrows in the CMG configuration model shown in Figure 4-1 depict the angular momentum vectors $\{h_i\}$ of the six gyros, all of approximately equal magnitude. These vectors are shown in their respective reference directions in the figure. The notation used in describing the configuration angles is shown in Figure 4-2. All gimbal axes are tilted at an angle β from the x-axis, and the projections of the gimbal axes on the yz-plane are directed at angles $\gamma = \{0, 60, 120, 180, 240, 300\}$ degrees from the y-axis. The gimbal angles denoted by $\alpha = \{\alpha_1, \dots, \alpha_6\}$ are measured from their respective reference directions in the counterclockwise direction about the gimbal axes as shown by

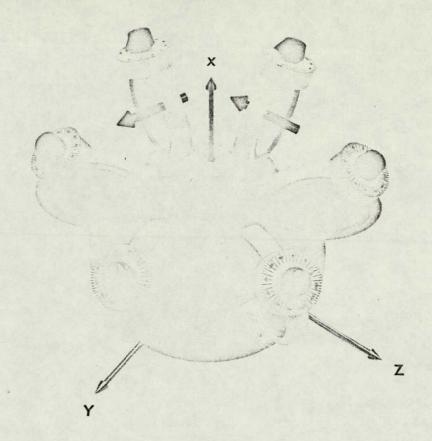


FIG. 4-1 Model of the Sperry 6-GAMS configuration.

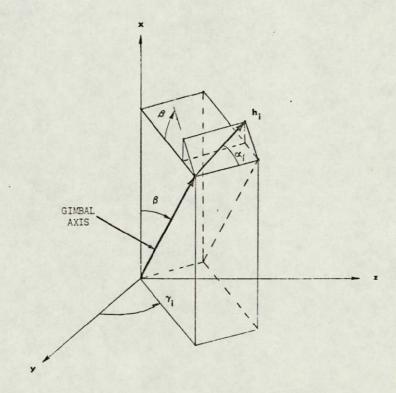


FIG. 4-2 CMG configuration reference system.

the angular scales of each gyro in Figure 4-1. For $\alpha = \{0, ..., 0\}$, the net angular momentum vector, H, of the CMG configuration is zero, assuming that all the individual momenta, $\{h_i\}$, are of equal magnitude. In general, the projections of \overrightarrow{H} onto the vehicle principal axes are given by equations (4.1), where $S_{(\)}$ denotes sin () and $C_{(\)}$ denotes cos ().

$$H_{\mathbf{X}} = \sum_{i=1}^{6} h_{i} S_{\beta}S_{\alpha_{i}}$$

$$H_{\mathbf{y}} = \sum_{i=1}^{6} -h_{i} \left(S_{\gamma_{i}}C_{\alpha_{i}} + C_{\beta_{i}}C_{\gamma_{i}}S_{\alpha_{i}}\right)$$

$$H_{\mathbf{z}} = \sum_{i=1}^{6} h_{i} \left(C_{\gamma_{i}}C_{\alpha_{i}} - C_{\beta_{i}}S_{\gamma_{i}}S_{\alpha_{i}}\right)$$

$$(4.1)$$

Equations (4.1) do not include the angular momentum due to the rotations of the gimbals and rotors about the gimbal axes which, for the purpose of steering law computations, may be assumed to be negligibly small in comparison with the angular momentum due to the rotation of the rotors about their spin axes.

CMG systems provide attitude control by appropriate transfer of angular momentum between the CMG'S and the vehicle. The mathematical law by which desired vehicle angular accelerations (or torques) are translated to gimbal rates is referred to as a steering law.

4.2.2 CMG Steering Laws

The equation of rigid-body angular motion for the vehicle (not including the CMG rotors and gimbals) is given by

$$T_{\mathbf{v}} = I_{\mathbf{v}} \stackrel{\bullet}{\omega} + \Omega I_{\mathbf{v}} \omega \tag{4.2}$$

where

 $T_v = 3 \times 1$ matrix of projections (onto the vehicle principal axes) of the net torque vector \vec{T}_v acting on the vehicle

 I_{v} = diagonal matrix of vehicle inertias about the principal axes

 $\omega = 3 \times 1$ matrix of projections of the vehicle rate vector $\vec{\omega}$

 $\dot{\omega}$ = 3 x 1 matrix of projections of the vehicle acceleration $\overrightarrow{\omega}$

$$\Omega = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$
(4.3)

Similarly, the equation of motion for each CMG rotor can be expressed in terms of angular momentum as

$$T_{R_{i}} = H_{i} + \Omega H_{i}$$
 (4.4)

where $T_{R_{\underline{i}}}$ and $H_{\underline{i}}$ are the 3 x 1 matrices of projections of the torque and angular nomentum vectors, respectively, for CMG number i. The net torque, T, produced by all six CMG's on the vehicle, neglecting gimbal inertias, is then given by

$$T = -\sum_{i=1}^{6} T_{R_{i}}$$

$$= -H - \Omega H$$
(4.5)

where

$$H = \sum_{i=1}^{6} H_{i} . {4.6}$$

By the law of conservation of angular momentum,

$$I_{v} \omega + H = H_{n} \tag{4.7}$$

where

$$H_{n} = I_{v}\omega_{o} + \int_{0}^{t} I_{d}dt^{\dagger}$$
 (4.8)

 H_n = net angular momentum of the vehicle plus the CMG's

 $\omega_0 = \omega$ at time t = o

 T_d = torque acting on the vehicle not caused by the CMG,

i.e.,
$$T_v = T + T_d$$
.

The CMG system is normally initialized so that H is close to zero when $\omega=0$; i.e., ω_0 is normally close to zero.

From the previous equations, the vehicle angular acceleration is given by

$$\dot{\mathbf{w}} = -\mathbf{I}_{\mathbf{v}}^{-1} \left[\dot{\mathbf{H}} + \Omega \left(\mathbf{H}_{\mathbf{n}} \right) + \mathbf{T}_{\mathbf{d}} \right]$$

$$\approx -\mathbf{I}_{\mathbf{v}}^{-1} \quad \dot{\mathbf{H}} \quad . \tag{4.9}$$

This approximation becomes an equality if $\omega_0=0$ and $T_d=0$. The vehicle acceleration, ω , can thus be controlled by controlling \dot{H} . If \dot{H} can be controlled so that

$$\dot{\mathbf{H}} = -\mathbf{I}_{\mathbf{v}} \dot{\hat{\mathbf{n}}}_{\mathbf{c}} \tag{4.10}$$

where $\omega_{\mathbf{c}}$ is a commanded ω , the torque produced on the vehicle by the CMG's is given by

$$T = I_{\mathbf{v}} \stackrel{\circ}{\mathbf{e}} + \Omega I_{\mathbf{v}} \left(\omega - \omega_{\mathbf{n}} \right)$$
 (4.11)

where $\omega_n = I_v^{-1} H_n$, the vehicle rate not caused by the CMG system. For $\omega_n \approx 0$, the CMG system thus inherently compensates for the centrifugal couple, $\Omega I_v \omega$, produced when ω has components in two or more of the principal axes for vehicles with unequal inertias.

By taking the time-derivatives of the components of H, given in equations (4.1) for the 6-GAMS configuration, H can be expressed by

$$H = A \alpha \tag{4.12}$$

where A is a 3 x 6 matrix of elements, $\alpha_{i,j}$, given by

$$\alpha_{1J} = h_{j} S_{\beta} C_{\alpha_{j}}$$

$$\alpha_{2j} = h_{j} \left(S_{\gamma_{j}} S_{\alpha_{j}} - C_{\beta} C_{\gamma_{i}} C_{\alpha_{i}} \right)$$

$$\alpha_{3j} = -h_{j} \left(C_{\gamma_{j}} S_{\alpha_{j}} + C_{\beta} S_{\gamma_{j}} C_{\alpha_{j}} \right)$$

$$(4.13)$$

for the stated configuration. Thus, the matrix A is a function of the gimbal angles $\alpha = \{\alpha_1, \dots, \alpha_6\}$.

H can therefore be controlled by controlling the gimbal rates, α . To control H according to equation (4.10), a solution of equation (4.12) is required. Since A is singular, any solution that exists is not unique. The specific solution that is adopted for a CMG system, even if it is only an approximate solution, is commonly referred to as the CMG steering law.

The selection of a steering law significantly affects the sizing (magnitude of h_1) required for the CMG's in order for the system to be able to meet a specified angular momentum envelope requirement. The most prominent steering law is based on the pseudo-inverse 2,3 of A and is referred to as the

pseudo-inverse steering law. The significant feature of this inverse, denoted by A^{\dagger} , is that it provides the unique minimum norm solution if a solution exists. In this case, A^{\dagger} can be computed by

$$A^{\dagger} = A^{T} \left(AA^{T}\right)^{-1} . \tag{4.14}$$

In minimizing the norm of the gimbal rates, this steering law tends to emphasize the gimbal rates of the CMG's that most efficiently provide momentum transfer in the commanded direction, thereby tending to maximize the net angular momentum envelope obtainable for the CMG configuration. Although other steering laws have been investigated (such as the superposition of solutions for three CMG's, and the transpose steering law which provides a very approximate solution), they have been found to be either less efficient with no simplification in the computations, or very inefficient with considerable computational simplification. It may be possible to improve on the pseudo-inverse steering law to increase the efficiency of angular momentum utilization even further, but a study to identify such a law is beyond the scope of this project. Without further justification, the pseudo-inverse steering law is selected for the CMG control computer described in this report.

The steering law computations thus provide gimbal rate commands, α_c , to the individual gimbal control systems in response to vehicle angular acceleration commands, $\dot{\omega}_c$, in accordance with the following equation:

$$\dot{\alpha}_{c} = A^{\dagger} \ddot{\mathbb{H}} = -A^{\dagger} \mathbf{I}_{v} \dot{\alpha}_{c} . \tag{4.15}$$

4.2.3 The Rate Gyro Configuration

The vehicle rate information required for attitude control system stability and/or vehicle rate control is to be obtained from a set of six rate gyros configured to sense vehicle rates along the six dodecahedron axes shown in Figure 4-3. These axes correspond to the normals of the faces of a regular dodecahedron and have the unique property that the acute angles between any two axes are equal, given by $28\approx63.4$ degrees. This configuration is described by Gilmore The significant feature of this sensor configuration is that the vehicle rates can be obtained from any three of the six dodecahedron rates, denoted by $r = \{r_1, \dots, r_6\}$.

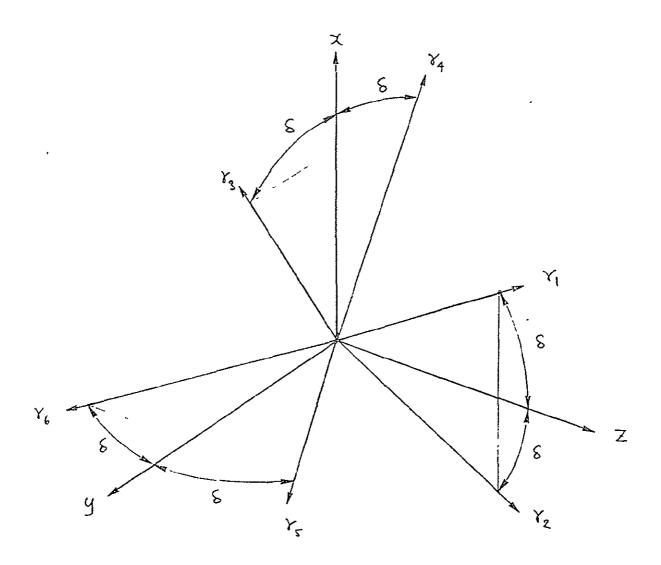


FIG. 4-3 Dodecahedron axis system.

The vehicle rates, o, can be projected onto the dodecahedron axes to obtain the dodecahedron rates r by

$$\mathbf{r} = \mathbf{E} \, \mathbf{\omega} \tag{4.16}$$

where

$$\mathbf{E} = \begin{bmatrix}
s & o & c \\
-s & 0 & c \\
c & s & o \\
c & -s & 0 \\
0 & c & s \\
o & c & -s
\end{bmatrix}$$
(4.17)

and

$$s = \sin \delta = \left(\frac{5 - \sqrt{5}}{10}\right)^{1/2} \approx 0.526$$

$$c = \cos \delta = \left(\frac{5 + \sqrt{5}}{10}\right)^{1/2} \approx 0.850 \quad . \tag{4.18}$$

If all six rate gyros are operating properly, the signals they generate, denoted by r_s , are approximately equal to r. If a failure is detected in rate gyro number 1, however, this gyro is disengaged; i.e., $r_{si} = 0$. Let

$$\lambda = \operatorname{diag} \left\{ \lambda_1, \dots, \lambda_6 \right\} \tag{4.19}$$

where λ_i = 1 if rate gyro number i is engaged, and λ_i = 0 if it is disengaged. Then

$$\mathbf{r}_{S} = \lambda \mathbf{r} = \mathbf{E} \omega \tag{4.20}$$

where $E=\lambda\overline{E}$. To determine ω from r_s requires the solution of equation (4.20) Although E is a constant matrix for every state of λ , there are 42 states of λ for which at least three of its elements are 1's; and there are 20 states for which exactly three of its elements are 1's. Therefore, at least 20 different solutions are required in order to find ω under all failure conditions (up to three failures).

Since any three rate gyros contain sufficient information to find ω , only the 20 solutions are required to meet all failure conditions. By using all the rate gyros available, however, the effects of inaccuracies in the signals can be minimized. The pseudo-inverse solution given by equations (4.21) and (4.22) provides the solution for ω that minimizes the norm of $\lambda r - r_s$ (the "least-squares-fit" solution)

$$\omega_{S} = E^{\dagger} r_{S} \tag{4.21}$$

where

$$E^{\dagger} = \left(E^{T}E\right)^{-1} E^{T}$$

$$= \left(\bar{E}^{T}\lambda\bar{E}\right)^{-1} \left(\bar{E}^{T}\lambda\right)$$
(4.22)

and where ω_s is the set of sensed and transformed signals for ω . This solution is identical to a three-signals-only solution when all but the three respective elements of λ are set to zero.

The detection and isolation of failures in the rate gyro package is also a major task for the CMG control computer in order to generate λ . Catastrophic failures can usually be detected by various types of monitors, but errors in the signals are not as easy to detect. Gilmore describes a set of parity equations that isolate two gyro failures and detect a third failure. These equations are presented in Table 4.1 under the notational convention adopted for this report.

TABLE 4.1
Parity Equations for Rate Gyro Failure
Detection and Isolation

		,		
Equation No.	Equation	Signals Compared		
1	$(r_1 - r_2) c - (r_3 + r_4) s = 0$	1234		
2	$(r_2 + r_3) c - (r_1 + r_5) s = 0$	1235		
3	$(r_3 - r_1) c + (r_2 - r_6) s = 0$	1236		
14	$(r_{1} - r_{1}) c + (r_{2} - r_{5}) s = 0$	1245		
5	$(r_2 + r_1) c - (r_1 - r_6) s = 0$	1246		
6	$(r_5 - r_6) c - (r_1 + r_2) s = 0$	1256		
7	$(r_1 + r_5) c - (r_1 - r_3) s = 0$	1345		
8	$(r_6 - r_3) c + (r_1 + r_4) s = 0$	1346		
9	$(r_1 + r_6) c - (r_3 + r_5) s = 0$	1356		
10	$(r_5 - r_1) c + (r_4 - r_6) s = 0$	1456		
11	$(r_5 - r_3) c + (r_4 - r_2) s = 0$	2345		
12	$(r_6 + r_{1+}) c + (r_2 - r_3) s = 0$	2346		
13	$(r_2 - r_5) c + (r_3 + r_6) s = 0$	2356		
14	$(r_2 + r_6) c + (r_4 - r_5) s = 0$	2456		
15	$(r_4 - r_3) c + (r_5 - r_6) s = 0$	3456		

4.2.4 Control Computer Description

The principal function of the CMG control computer is to generate gimbal rate command signals to the six CMG's of the configuration described in paragraph 4.2.1, such that the vehicle responds in accordance with input command signals for vehicle rate and acceleration, using the rate signals provided by the six dodecahedron configured rate gyros described in paragraph 4.2.3. An objective of the computer structure is to take advantage of the redundancy in both the CMG and rate gyro configurations to provide fail-operational performance, including failures in the computer.

The control law for the vehicle rate control system, illustrated in Figure 4-4 can be written in the form

$$\dot{\omega}_{c} = \dot{\omega}_{cc} + G^{3} \left(\omega_{c} - \omega_{s} \right) \tag{4.23}$$

where

cc = vehicle acceleration commanded directly as an input to the rate control system

 $\omega_c - \omega_s = \text{vehicle rate error}$

 $G^3 = 3 \times 3$ diagonal matrix of compensation functions

The input signals ω_{cc} and ω_{c} are provided either by a control law for the vehicle attitude control system or by manual commands. The vehicle rate signal ω_{s} is obtained by converting the six dodecahedron axes rate signals r_{s} to vehicle axes signals.

Since both the sensor signals r_s and the gimbal rate command signals $\dot{\sigma}_c$ are 6-tuples, the question has been raised as to whether there are any advantages in performing the computations in six variables without first reducing the rate signals to the three-variable format. It has been suggested that by performing computations of data in a redundant format, perhaps some reliability advantage can be obtained with incremental computers, for which simultaneous computations are performed by separate components. The thought is that if one or more of such components should fail without affecting the remainder of the computations, the redundancy of the data and the computations would permit fail-operational performance. Investigations into this approach indicate that fail-operational performance is obtainable for certain component failures, but the complexity of such a system is considerably greater than for a system with redundancy at the overall computer level. In addition, there are many types of computer failures that do not permit fail-operational performance. Two complete

computers with failure monitoring or three such computers with majority voting provide greater reliability and appear to be less complex for reasons discussed subsequently.

The vehicle accelerations in the dodecahedron axes for which rate gyro signals are available, $\lambda \hat{\mathbf{r}}$, can be related to gimbal rates by combining equations (4.9), (4.12) and (4.20) to obtain

$$\lambda \dot{\mathbf{r}} = -R\dot{\alpha} \tag{4.24}$$

here

$$R = EI_{v}^{-1}A \qquad (4.25)$$

and where the disturbance terms of equation (4.9) are neglected for simplicity. The steering law in this case is required to solve equation (4.24) for α_c in terms of vehicle acceleration command signals \dot{r}_c in the six-variate format. This command signal is given by

$$\dot{\mathbf{r}}_{\mathbf{c}} = \mathbf{E}\dot{\mathbf{n}}_{\mathbf{c}} \tag{4.26}$$

and for the vehicle rate control law of equation (4.22)

$$\dot{\mathbf{r}}_{c} = \mathbf{E}\dot{\mathbf{n}}_{cc} + \mathbf{E} \mathbf{G}^{3} \left(\mathbf{n}_{c} - \mathbf{n}_{s}\right) . \tag{4.27}$$

By requiring that the three diagonal elements of G^3 be identical, thereby requiring that the control system characteristic be identical in the three vehicle exes, the product E G^3 can be written as G^6 E, where G^6 is a diagonal 6 x 6 natrix having diagonal elements identical to G^3 . Equation (4.27) can then be written as

$$\dot{\mathbf{r}}_{c} = E\dot{\mathbf{n}}_{cc} + G^{6} \left(E\mathbf{n}_{c} - \mathbf{r}_{s} \right)$$

$$= \dot{\mathbf{r}}_{cc} + G^{6} \left(\mathbf{r}_{c} - \mathbf{r}_{s} \right) . \tag{4.28}$$

Figure 4-5 shows the structure for this control law.

The steering law in this case is required to invert the 6 x 6 matrix R and the pseudo-inverse is selected for the reasons given in paragraph 4.2.2. The simplest method for computing the pseudo-inverse of a 6 x 6 matrix of rank 3 is to first factor it into the product of a 6 x 3 matrix M times a 3 x 6 matrix N, which is always possible 6. The pseudo-inverse S of R = MN can then be computed by

$$S = R^{\dagger} = N^{T} \left(NN^{T}\right)^{-1} \left(M^{T}M\right)^{-1} M^{T} . \tag{4.29}$$

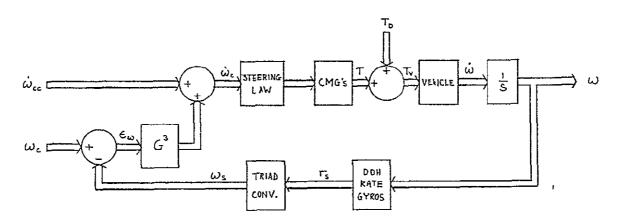


FIG. 4-4 Three-variate control law.

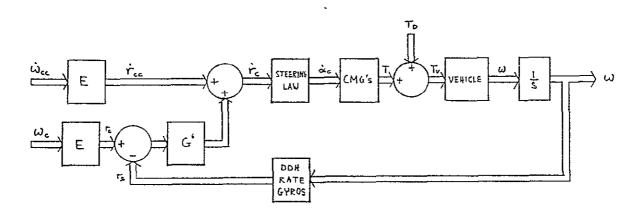


FIG. 4-5 Six-variate control law.

Some authors define the pseudo-inverse by equation (4.29). Therefore

$$S = N^{\dagger} M^{\dagger} \tag{4.30}$$

S can be factored as follows to obtain

$$S = \begin{pmatrix} -1 \\ I_V \end{pmatrix}^{\dagger} E^{\dagger}$$
$$= A^{\dagger} I_V E^{\dagger} . \tag{4.31}$$

Although there are infinitely many ways of factoring R to obtain the unique $S=R^{\uparrow}$, equation (4.30) indicates that the pseudo-inverse of this 6 x 6 matrix is equivalent to a transformation of the six-variate acceleration commands \dot{r}_{c} to some three-axis format, followed by a transformation to the six-variable gimbal rate commands \dot{a}_{c} . The question is whether implementation of the 6 x 6 matrix S can provide any advantages in terms of simplicity or reliability over cascading the 6 x 3 and 3 x 6 matrix factors of S.

Direct computation of the elements of S can provide limited failoperational performance if such failures can be detected and isolated. By expanding the steering law computations

$$\dot{a}_{c} = -S \dot{r}_{c} \tag{4.32}$$

to obtain

$$\dot{a}_{c1} = -s_{11} \dot{r}_{c1} - s_{12} \dot{r}_{c2} - \cdots - s_{16} \dot{r}_{c6}$$

$$\dot{a}_{c2} = -s_{21} \dot{r}_{c1} - s_{22} \dot{r}_{c2} - \cdots - s_{26} \dot{r}_{c6}$$

$$\cdots$$

$$\dot{a}_{c6} = -s_{61} \dot{r}_{c1} - s_{62} \dot{r}_{c2} - \cdots - s_{66} \dot{r}_{c6}$$
(4.33)

it can be observed that the effects of a failure in the computation of the element, S_{ij} , can be nullified by letting $\lambda_j = 0$, thus causing \dot{r}_{cj} to be zero. The steering law is a function of λ , and is therefore automatically modified to compensate for this step. Since the elements of column j in S are nullified by this procedure, isolated computation of the elements of this column is required. However, all 18 elements of A^{\dagger} must be computed for each of the six columns of S, necessitating six isolated computations of these elements, each element being a relatively complex function of the six gimbal angles. An increase in these computations, which constitute the bulk of the steering law computations, by a

factor of six represents a very significant increase in the complexity of the entire computer. Yet it provides fail-operational performance for only a limited set of failure types, namely those failures which can be isolated to the computation of the elements of a column. Further use of the rate gyro corresponding to the failed column is unfortunately also nullified by this procedure, thereby reducing the redundancy of the rate gyro package.

To perform steering law computations on the six-variable signals also requires conversion of the three-variate input command signals, $\dot{\omega}_{cc}$ and ω_{c} , to \dot{r}_{cc} and r_{c} . In addition, six rate-loop compensation filters are required instead of the three required with the three-variable system.

Based on these observations, it appears that parallel redundancy of the entire computer is preferred both from standpoints of complexity and reliability. The remainder of this report, therefore, considers only the three-variate structure for the control law.

Figure 4-6 shows the basic structure for the CMG control system in terms of its subcomputers, the CMG configuration, the vehicle, and the rate gyro package. Redundancy in the computation is not shown; this aspect is discussed in the following section.

4.2.5 Fail-Operational Computation

Fail-operational performance for a computation function can be obtained with two or more complete channels of computation plus monitors that are able to detect and identify a channel failure. In some cases, the only reliable technique for identifying a failure is to "vote" between at least three channels for a single failure, at least four channels for two failures, and so on. If it is possible to reliably detect a failure in a single channel by a simple method, one less channel of computation is required in comparison with the voting method. It is therefore worthwhile to investigate techniques for failure monitoring.

The steering law computation and the dodecahedron inversion both consist of the inversion of matrices that are very much simpler to compute in the forward direction than to invert. By performing the forward transformation M on the output of an inversion transformation M[†] and comparing the resulting output with the original input, an indication of a failure in either of these transformations is obtained. This principle is illustrated in Figure 4-7.

The scope of this study does not permit comparisons of various methods for detecting and isolating failures, and the approach suggested here requires further study.

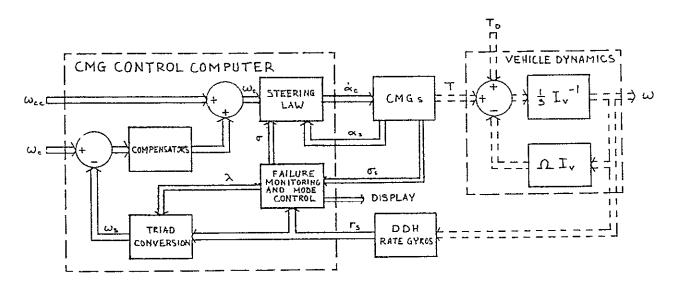


FIG. 4-6 CMG control system block diagram.

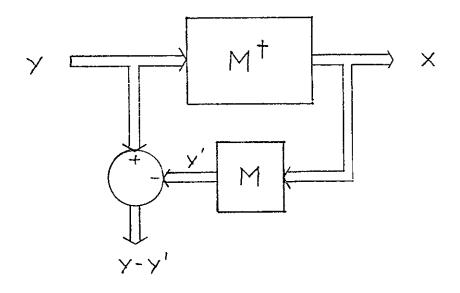


FIG. 4-7 Method of failure detection.

4.3 STEERING LAW COMPUTATION

Since the steering law computation is by far the most complex function to be performed by the CMG control computer, most of the effort under this program has been devoted to this function. Paragraph 4.3.1 presents the equations to be computed by the steering law computer, paragraph 4.3.2 describes the principles of incremental computation, and the remaining paragraphs describe how the equations can be implemented with incremental computation.

4.3.1 Equations and Computer Structure

The steering law computer is required to generate gimbal rate command signals $\overset{\circ}{\alpha}_{C}$ to the individual gimbal control systems of the CMG's in response to vehicle angular acceleration signals $\overset{\circ}{\omega}_{C}$ in accordance with equations given in paragraph 4.2.2 and repeated below for convenience

$$\dot{\alpha}_{c} = -A^{\dagger} I_{v} \dot{\omega}_{c}$$

$$\dot{\alpha}_{c} = \begin{bmatrix} \dot{\alpha}_{c1} \\ \dot{\alpha}_{c2} \\ \dot{\alpha}_{c3} \\ \dot{\alpha}_{c4} \\ \dot{\alpha}_{c5} \\ \dot{\alpha}_{c6} \end{bmatrix} \quad \dot{\omega}_{c} = \begin{bmatrix} \dot{\omega}_{cx} \\ \dot{\omega}_{cy} \\ \dot{\omega}_{cy} \\ \dot{\omega}_{cz} \end{bmatrix}$$

$$I_{v} = \begin{bmatrix} I_{x} & O & O \\ O & I_{y} & O \\ O & O & I_{z} \end{bmatrix}$$

 I_x , I_y , and I_z are the inertias of the vehicle about its principal axes, and $\left[A^{\dagger} = A^{T} (AA^{T})^{-1} \right]$ is the pseudo-inverse of A.

To simplify notations in the subsequent development, the following definitions are made.

$$B = AA^{T}$$
 (4.34)

$$C = \text{adj } B \tag{4.35}$$

$$d_{O} = \det B \tag{4.36}$$

$$D = A^{T}C \tag{4.37}$$

$$u = \left(\frac{1}{d_o}\right) \left(I_v \dot{\omega}_c\right) . \tag{4.38}$$

Then,

$$A^{\dagger} = D \left(\frac{1}{\bar{d}_{o}} \right) \tag{4.39}$$

anđ

$$\dot{a}_{c} = -Du \quad \cdot \tag{4.40}$$

By leaving A^{\dagger} in the factored form, as in equation (4.39) only three divisions by the scalar d_0 are required compared to 18 such divisions if the elements of A^{\dagger} were to be computed. Since B is only a 3x3 matrix, the adjoint method for inverting B is used. The steering law computer can now be structured of subcomputers related to the above defined variables so that they can be discussed separately. Figure 4-8 illustrates this structure of the steering law computer.

The A computer computes the elements of A given by

$$a_{ij} = h_{j} S_{\beta} C_{\alpha j}$$

$$a_{2j} = h_{j} \left(S_{\gamma j} S_{\alpha j} - C_{\beta} C_{\gamma j} C_{\alpha j} \right)$$

$$a_{3j} = -h_{j} \left(C_{\gamma j} S_{\alpha j} + C_{\beta} S_{\gamma j} C_{\alpha j} \right).$$

$$(4.41)$$

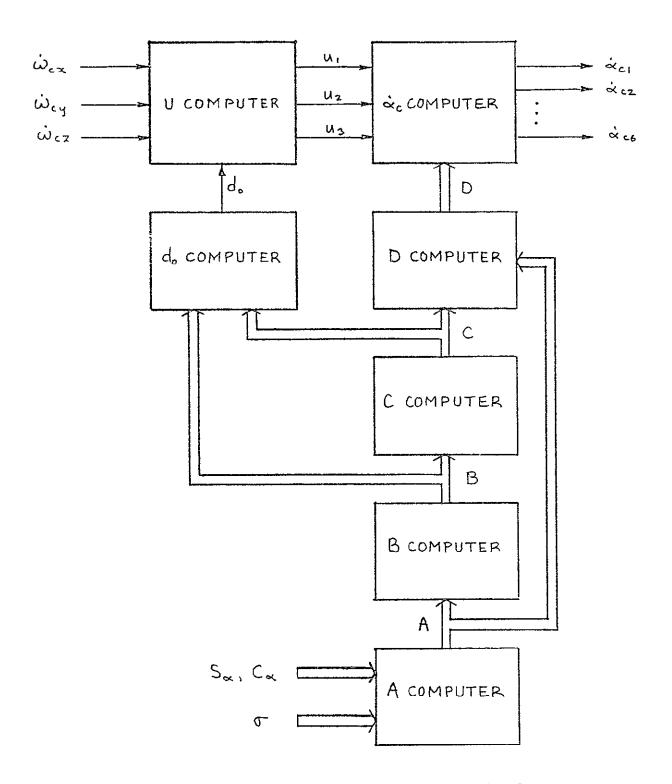


FIG. 4-8 Organization of the pseudo-inverse steering law computer.

Element aij may be factored into

$$a_{ij} = \rho_{ij}\sigma_{j} \tag{4.42}$$

where

$$\rho_{ij} = \left(m_{ij} S_{\alpha_{j}} + m_{ij} C_{\alpha_{j}} \right) \tag{4.43}$$

and where o is the speed of rotor is in revolutions per second. The constants $\mathbf{m_{i,j}}$ and $\mathbf{n_{i,j}}$ are given by

$$m_{1j} = 0$$
 $n_{1j} = 2\pi I_R S_{\beta}$
 $m_{2j} = 2\pi I_R S_{\gamma j}$ $n_{2j} = -2\pi I_R C_{\beta} C_{\gamma j}$
 $m_{3j} = -2\pi I_R C_{\gamma j}$ $n_{3j} = -2\pi I_R C_{\beta} S_{\gamma j}$ (4.44)

where I_R is the inertia of the CMG rotor about its spin axis. For the 6-GAMS configuration described in paragraph 4.2.1, the γ angles are 0, 60, 120, 180, 240, and 300 degrees so $\left\{S_{\gamma_j}\right\}$ and $\left\{C_{\gamma_j}\right\}$ are specified, but the gimbal axis tilt angle β depends on the requirements for the net angular momentum envelope.

Thus, the A computer for each of the 18 elements $\{a_{ij}\}$ performs the scaling and addition of the input signals, $S_{\alpha j}$ and $C_{\alpha j}$, as indicated by equation (14.3-10) and multiplies the result by the input signal for rotor speed, σ_{j} .

To help visualize the complexity associated with each of the subcomputers of the steering law computer, the related matrix expressions are expanded in the following discussion. Since $B = AA^{\dagger}$ is a symmetric 3x3 matrix, only six elements such as those making up the upper triangle of B, are required. These elements are

$$b_{11} = a_{11}^{2} + a_{12}^{2} + a_{13}^{2} + a_{14}^{2} + a_{15}^{2} + a_{16}^{2}$$

$$b_{12} = a_{11}a_{21} + a_{12}a_{22} + a_{13}a_{23} + a_{14}a_{24} + a_{15}a_{25} + a_{16}a_{26}$$

$$b_{13} = a_{11}a_{31} + a_{12}a_{32} + a_{13}a_{33} + a_{14}a_{34} + a_{15}a_{35} + a_{16}a_{36}$$

$$b_{22} = a_{21}^{2} + a_{22}^{2} + a_{23}^{2} + a_{24}^{2} + a_{25}^{2} + a_{26}^{2}$$

$$b_{23} = a_{21}a_{31} + a_{22}a_{32} + a_{23}a_{33} + a_{24}a_{34} + a_{25}a_{35} + a_{26}a_{36}$$

$$b_{33} = a_{31}^{2} + a_{32}^{2} + a_{33}^{2} + a_{34}^{2} + a_{35}^{2} + a_{36}^{2}$$

$$(4.45)$$

The C computer evaluates the upper triangle elements of C = adj B since this matrix is also symetric:

$$c_{11} = b_{22}b_{33} - b_{23}^{2}$$

$$c_{12} = b_{13}b_{23}^{**} - b_{12}b_{33}$$

$$c_{13} = b_{12}b_{23} - b_{13}b_{22}$$

$$c_{22} = b_{11}b_{33} - b_{13}^{2}$$

$$c_{23} = b_{12}b_{13} - b_{11}b_{23}$$

$$c_{33} = b_{11}b_{22} - b_{12}^{2}$$
(4.46)

Elements of B and C are used to compute do:

$$d_0 = b_{11}c_{11} + b_{12}c_{12} + b_{13}c_{13}$$
 (4.47)

The 18 elements of $D = A^{T}C$ are computed as follows:

$$d_{11} = a_{11}c_{11} + a_{21}c_{12} + a_{31}c_{13}$$

$$d_{12} = a_{11}c_{12} + a_{21}c_{22} + a_{31}c_{23}$$

$$d_{13} = a_{11}c_{13} + a_{21}c_{23} + a_{31}c_{33}$$

$$d_{21} = a_{12}c_{11} + a_{22}c_{12} + a_{32}c_{13}$$

$$d_{22} = a_{12}c_{12} + a_{22}c_{22} + a_{32}c_{23}$$

$$d_{23} = a_{12}c_{13} + a_{22}c_{23} + a_{32}c_{33}$$

$$d_{31} = a_{13}c_{11} + a_{23}c_{12} + a_{33}c_{13}$$

$$d_{32} = a_{13}c_{12} + a_{23}c_{22} + a_{33}c_{23}$$

$$d_{33} = a_{13}c_{13} + a_{23}c_{22} + a_{33}c_{23}$$

$$d_{41} = a_{14}c_{11} + a_{24}c_{12} + a_{34}c_{13}$$

$$d_{42} = a_{14}c_{12} + a_{24}c_{22} + a_{34}c_{23}$$

$$d_{43} = a_{14}c_{13} + a_{24}c_{22} + a_{34}c_{23}$$

$$d_{51} = a_{15}c_{11} + a_{25}c_{12} + a_{35}c_{13}$$

$$d_{52} = a_{15}c_{12} + a_{25}c_{22} + a_{35}c_{23}$$

$$d_{53} = a_{15}c_{13} + a_{25}c_{23} + a_{35}c_{33}$$

$$d_{61} = a_{16}c_{11} + a_{26}c_{12} + a_{36}c_{13}$$

$$d_{62} = a_{16}c_{12} + a_{26}c_{22} + a_{36}c_{23}$$

$$d_{63} = a_{16}c_{13} + a_{26}c_{23} + a_{36}c_{33}$$

$$d_{63} = a_{16}c_{13} + a_{26}c_{23} + a_{36}c_{33}$$

The only divisions required in the steering law computer are in the u computer. The elements of this 3 x 1 matrix are

$$u_{1} = \frac{I_{x}\dot{\omega}_{cx}}{d_{o}}$$

$$u_{2} = \frac{I_{y}\dot{\omega}_{cy}}{d_{o}}$$

$$u_{3} = \frac{I_{z}\dot{\omega}_{cz}}{d_{o}}$$
(4.49)

The $\mathring{\alpha}_{_{\mathbf{C}}}$ computer then provides the outputs of the steering law computer by performing the following computations

$$\dot{a}_{c1} = d_{11}u_{1} + d_{12}u_{2} + d_{13}u_{3}$$

$$\dot{a}_{c2} = d_{21}u_{1} + d_{22}u_{2} + d_{23}u_{3}$$

$$\dot{a}_{c3} = d_{31}u_{1} + d_{32}u_{2} + d_{33}u_{3}$$

$$\dot{a}_{c4} = d_{41}u_{1} + d_{42}u_{2} + d_{43}u_{3}$$

$$\dot{a}_{c5} = d_{51}u_{1} + d_{52}u_{2} + d_{53}u_{3}$$

$$\dot{a}_{c6} = d_{61}u_{1} + d_{62}u_{2} + d_{63}u_{3}$$

$$\dot{a}_{c6} = d_{61}u_{1} + d_{62}u_{2} + d_{63}u_{3}$$

A summary of the types and numbers of mathematical operations required for the subcomputations of the steering law computer is presented in Table 4.2.

TABLE 4.2

Nathematic Operations for the Steering Law Computer

Subcomputer	Additions	Multiplications	Divisions		
A	18	18	0		
В	30	36	0		
C	6	12	0		
ďo	2	3	0		
D	36	5 ¹ +	0		
u	0	0	3		
άc	12	18	0		
Total	104	141	3		

+.3.2 Incremental Computation

An incremental computer is a special purpose digital computer that has a number of features which make it attractive for solving equations of the type required for the pseudo-inverse steering law. In contrast with the general purpose type digital computer, which performs entire computations during each computation cycle, an incremental computer updates previous computations. Such computations are generally much simpler and are performed simultaneously on the numerous variables of the problem. The time required to complete each computation cycle is therefore much less than for a general purpose computer, permitting higher sampling rates.

In an incremental computer, the variables of the computations are stored in binary registers, referred to as Y registers. The content (numerical value) stored in a Y register is increased by one when so commanded by a pulse, ΔY , representing an incremental increase in the variable Y. The ΔY pulse can also be negative, in which case the Y register is decreased by one. In addition, the content of a Y register is added to the content of an R register when so commanded by a positive ΔX pulse, or it is subtracted from the R register for a negative ΔX pulse.

Figure 4.3-2 shows the schematic symbols adopted for the incremental computer elements. Since the R register has the same capacity as the Y register, repeated ΔX pulses of the same sign will cause the R register to overflow. Each time the R register overflows in the positive direction, a positive ΔZ pulse is generated; if the overflow is in the negative direction, a negative ΔZ pulse is generated. This ΔZ pulse can then serve as a ΔX pulse or a ΔY pulse for other Y and R registers. Let

$$Z(n) = \sum_{i=1}^{n} \Delta Z(i)$$
 (4.51)

where $\Delta Z(i)$ is the ΔZ pulse produced by the i'th ΔX pulse, $\Delta X(i)$ [$\Delta Z(i)$ may be 0, +1, or -1] ω Let Y(i) and R(i) be the contents of the Y and R registers, respectively, at the occurrence of $\Delta X(i)$, and let c be the capacity of the registers. Then

$$cZ(n) + R(n) = R(1) + \sum_{i=1}^{n} Y(i) \Delta X(i)$$
 (4.52)

Therefore, for |Y(i)| >> 1,

$$Z(n) \approx \frac{1}{c} \sum_{i=1}^{n} Y(i) \Delta X(i) . \qquad (4.53)$$

For the case where Y(i) is a function of X(i),

$$Z(n) \approx \frac{1}{c} \int_{0}^{X(n)} Y[X(i)] dX(i)$$
 (4.54)

This computation structure may thus be used to integrate functions of independent variables, and combinations of such elements may be used to generate functions that are solutions of differential equations. Computers structured by interconnecting integrators of this type are commonly referred to as DDA's (digital differential analyzers).

The computations for the steering law require only additions, multiplications, and divisions. The sum of several variables can be obtained by feeding their respective Δ pulses to a common Y register and properly controlling their pulse times so that they do not occur simultaneously. Such timing control can be implemented by various methods, and will be discussed later.

Multiplication is readily obtained by noting that

$$d(Y_1Y_2) = Y_1dY_2 + Y_2dY_1 (4.55)$$

Therefore, let $\Delta X_1 = \Delta Y_2$ and $\Delta X_2 = \Delta Y_1$, and let the two Y registers add into a common R register as shown in Figure 4-10. Then

$$\Delta Z \approx \frac{1}{c} \left(Y_1 \Delta Y_2 + Y_2 \Delta Y_1 \right) \approx \frac{1}{c} \Delta \left(Y_1 Y_2 \right) . \tag{4.56}$$

The accuracy of this computation improves with the size c of the registers. It can also be improved by proper sequencing of the operations when ΔY_1 and ΔY_2 occur simultaneously. Investigations of such methods are beyond the scope of this study.

4.3.3 <u>AA Computation</u>

The ΔA computer generates increments Δa_{ij} to increase or decrease the values in the set of 18 registers that store the elements of the A matrix, given by equations (4.42), (4.43) and (4.44). Column j of A corresponds to CMG number j. The incremental computer structure for the three elements of this column is shown in Figure 4-11.

The Y register corresponding to some variable, y, is identified by this variable, and it stores the numerical value $K_y y$ where K_y is a scale factor. The R register that generates Δy is identified by \widetilde{y} . Constant numbers are represented by the oval-shaped areas in Figure 4-11. For example, when a positive pulse for $\Delta \sigma_j$ occurs, the Y register containing $K_{\sigma_j} \sigma_j$ is increased by the constant number K_{σ_j} .

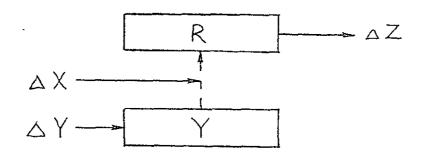


FIG. 4-9 Basic incremental computer elements.

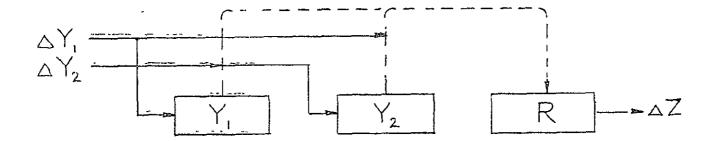


FIG. 4-10 Incremental multiplier.

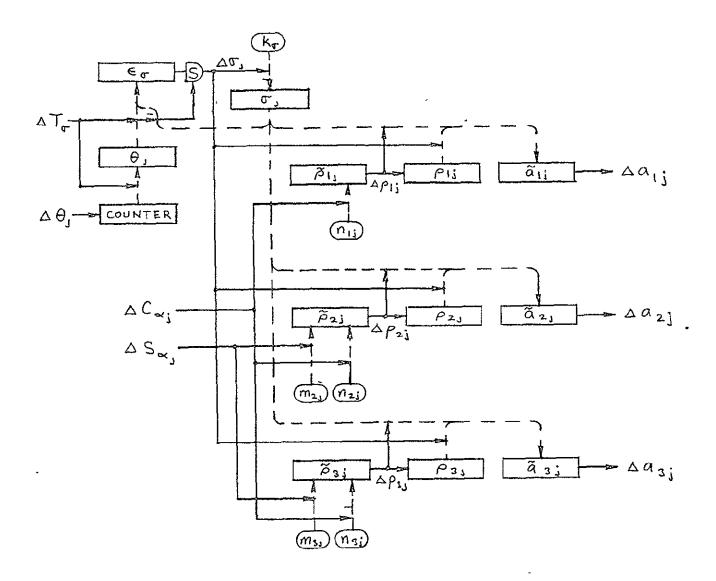


FIG. 4-11 $\triangle A$ computer.

The rotor speed σ_j (revolutions per second) can be held constant by the spin motor electronics to some degree of accuracy, but high accuracy may be difficult to achieve. If the rotor speed is sensed and included in the steering law computations, rotor speed control is not required at all, permitting simple spin motor electronics. The rotor speed is therefore included in the steering law computations.

The rotor speed is computed by counting revolutions θ_j over a period of time T_σ . A pulse $\Delta\theta_j$ produced for each rotor revolution increases the counter by one. A pulse ΔT_σ is produced each T_σ seconds by some clock. T_σ must be quite long, such as several seconds, to permit sufficient resolution in σ_j . When the ΔT_σ pulse occurs, the θ_j register is first set to K_θ , θ_j , where θ_j is the present number in the counter and where K_θ = K_σ / T_σ (chosen to be a power of 2 for simplicity). The counter is then reset to zero. Next, K_θ , θ_j and K_σ , are compared by adding the first to, and subtracting the second from, the ϵ_σ register. If this difference is positive, a positive $\Delta\sigma_j$ pulse is generated and causes the σ_j register to increase by K_σ , or vice versa for a negative pulse.

To obtain maximum accuracy in incremental computations, the Y registers should be scaled so low that they are as full as possible without overflowing. Therefore, K_{σ} is selected so that K_{σ} times maximum σ_{j} is close to but does not exceed the register capacity c.

 $T_{\sigma} \left(\text{or } K_{\theta_j} = K_{\sigma_j} / T_{\sigma} \right) \text{ should be selected to minimize the error in } \sigma_j. \quad \text{If } T_{\sigma} \text{ is very large, the maximum error in } \sigma_j \text{ due to resolution, given by } \sigma_j / \theta_j = 1 / T_{\sigma}, \text{ is small. However, the maximum error due to a change in } \sigma_j \text{ during the } T_{\sigma} \text{ interval, } \sigma_m T_{\sigma} \text{ (where } \sigma_m = \max \sigma, \text{ assumed constant in this interval), is large. The } T_{\sigma} \text{ for which these errors are equal is given by } T_{\sigma} = 1 / \sqrt{\sigma_m} \text{ .}$

Incremental signals for $\sin\alpha_j$ and $\cos\alpha_j$ can be obtained by numerous methods, but at the present state of the art a set of six resolvers with a single time-shared A/D converter for all six gimbal angles appears to be the test candidate. Selection of a preferred method is not performed under this study. The scale factor for the registers in the A/D converter that store S_{α_j} and C_{α_j} is K_{sc} ; i.e., a ΔS_{α_j} pulse corresponds to a change of $1/K_{sc}$ in S_{α_j} , etc.

When a positive $\Delta S_{\alpha j}$ pulse or $\Delta C_{\alpha j}$ pulse occurs, the $\tilde{\rho}_{1j}$ registers are increased by the respective constants, m_{ij} and m_{ij} . If this produces a positive overflow of a ρ_{1j} register, the resulting $\Delta \rho_{1j}$ pulse causes ρ_{ij} to increase by one, and σ_{ij} to be added to \tilde{a}_{ij} . Overflows in the \tilde{a}_{ij} registers then produce the output pulses of the ΔA computer, which are held in flip-flops until called for in the next computation cycle. Additions to the \tilde{a}_{ij} registers are also produced by a $\Delta \sigma_{ij}$ pulse.

Although there are many ways to perform the functional operations symbolized in Figure 4-11, considerable savings in hardware may be realized by serializing many of the variables on a single, long, circulating register. Table 4.3 describes one method for sequencing the additions into the \tilde{a}_{ij} registers. All 18 variables $\left\{\rho_{ij}\right\}$ are serialized on a single, long register in the sequence shown in the table, and the size variables $\left\{\sigma_{j}\right\}$ are serialized on a single register such that exactly three cycles of the σ register coincide with one cycle of the ρ register, and such that the least significant bits of σ_{1} , ρ_{11} , and \tilde{a}_{ij} coincide, etc, as shown. The 18 \tilde{a} registers are the same length as each word of ρ and σ . During word interval 1, the ρ register adds into the \tilde{a}_{11} register if $\Delta\sigma_{1}$ = 1 (or subtracts if $\Delta\sigma_{1}$ = -1), the σ register adds into \tilde{a}_{16} if $\Delta\rho_{16}$ = 1 (or subtracts if $\Delta\rho_{16}$ = -1), etc, as shown in the table. It is also possible to serialize the a_{ij} variable with increased logic complexity and longer cycle time.

- 64 -

TABLE 4.3
A Computation Sequence

Interval:	1	2	3	14	5	6	7	8	9	10	11	12	13	11+	15	16	17	18
ρı	^р 11	ρ ₂₁	ρ ₃₁	^P 12	P 22	ρ ₃₂	ρ ₁₃	P 23	P33	P14	P 214	P 314	ρ ₁₅	P 25	^ρ 25	^ρ 16	^p 26	P 36
σ:	σı	σ ₂	σ ₃	σ14	٥5	σ ₆	σ ₁	σ2	σ ₃	σ ₁ ₊	o 5	σ ₆	σ ₁	σ2	· σ ₃	۵,4	σ5	σ ₆
\$\tilde{a}_{11}\$\$\tilde{a}_{21}\$\$\tilde{a}_{31}\$\$\tilde{a}_{22}\$\$\tilde{a}_{32}\$\$\tilde{a}_{33}\$\$\tilde{a}_{14}\$\$\tilde{a}_{25}\$\$\tilde{a}_{34}\$\$\tilde{a}_{25}\$\$\tilde{a}_{36	^{σΔρ} 16 ^{σΔρ} 26 ^{σΔρ} 36		^{ρΔσ} 1	^{ρΔσ} 2	pΔσ ₂		σ ^Δ ρ ₂₁ σ ^Δ ρ ₃₁	^{σΔρ} 12 ^{σΔρ} 22 ^{σΔρ} 32		b⊽αJ†	ρ∆σ↓	ρΔσμ	ρ^σ 5			σδρ ₁ μ σδρ ₂ μ σδρ ₃ μ		

The Δa_{ij} pulses accumulate in the a_{ij} register (which is part of the ΔB computer). The number stored in this register is given by [per equation (4.56)]

$$K_{a_{1,j}} a_{i,j} = \frac{1}{c} \left(K_{\rho} \rho_{i,j} \right) \left(K_{\sigma} \sigma_{j} \right) . \tag{4.57}$$

Therefore, since $a_{ij} = \rho_{ij}\sigma_j$ [equation (4.42)]. the scale factors are required to satisfy

$$K_{a_{ij}} = \frac{K_{\rho_{ij}} K_{\sigma_{ij}}}{c}$$
 (4.58)

In addition, the Y registers cannot be allowed to overflow. Therefore,

$$K_{\rho_{ij}} \max |\rho_{ij}| \le c$$
 (4.59)

$$K_{\sigma_{ij}} \max |\sigma_{ij}| \le c$$
 (4.60)

$$K_{a_{ij}} \max |a_{ij}| \le c$$
 (4.61)

If more than one Δa_{ij} pulse is permitted to occur for each computation cycle, the complexity of the Δa_{ij} adder must be increased significantly. To avoid this situation, let

$$K_{\rho_{i,j}} \max \left| \rho_{i,j} \right| + K_{\sigma_{j}} \max \left| \sigma_{j} \right| \leq c$$
 (4.62)

Maximum accuracy is obtained with the scale factors as large as possible, subject to the above constraints.

Let the constants m_{ij} and m_{ij} have the same scale factor, $K_{m_{ij}}$. Then

$$K_{\rho_{1}j_{1}j_{1}} = \frac{1}{c} K_{m_{1}j} K_{sc} \left(m_{1}j_{\alpha_{j}} + n_{1}j_{\alpha_{j}} \right)$$
 (4.63)

Since $\rho_{ij} = m_{ij} s_{\alpha_{j}} + n_{ij} c_{\alpha_{j}}$ [equation (4.43)], the scale factors must satisfy

$$K_{\rho_{ij}} = \frac{K_{m_{ij}} K_{sc}}{c} \qquad (4.64)$$

Also, to prevent more than one $\Delta \rho_{i,j}$ pulse per computation cycle,

$$K_{m_{ij}} \left(\left| m_{ij} \right| + \left| n_{ij} \right| \right) \le c \tag{4.65}$$

4.3.4 AB Computation

The ΔB computer calculates the increments for the six upper triangle elements of the B matrix given in equations (4.45). Figure 4-12 shows the structure of this computer, which has 18 Y registers to store the A matrix elements and six R registers to generate the Δb_{ij} pulses.

Each of the three diagonal elements of B is the sum of the squares of the six elements in a row of A. By letting $\Delta X = \Delta Y$ (see Figure 4-9), we obtain

$$\Delta Z = \frac{1}{c} Y \Delta Y$$

$$\approx \frac{1}{2c} \Delta (Y^2) . \tag{4.66}$$

Therefore, by adding K a ij to K b bi when Δa = +1 for each j, the content of the Y register that accumulates the Δb_{ii} pulses will be

$$K_{b_{ij}}^* b_{ii} \approx \frac{1}{2} c \sum_{j=1}^{6} (K_{a_{ij}} a_{ij})^2$$
 (4.67)

In order for

$$b_{ii} = \sum_{j=1}^{6} a_{ij}^{2}$$
 (4.68)

the scale factors for the diagonal elements of B must satisfy

$$K_{b_{11}}^* = \frac{K_{a_1}^2}{2c}$$
 (4.69)

where $K_{a_i} = K_{a_{i,i}}$ for all j.

For the off-diagonal elements, multiplication is performed as described previously. In this case,

$$K_{b_{i,j}} = \frac{1}{c} \sum_{K=1}^{6} K_{a_{i}} K_{a_{j}} K_{a_{j}} k$$
(4.70)

Therefore,

$$K_{b_{ij}} = \frac{K_{a} \quad K_{a}}{1 \quad j}, \quad i \neq j \qquad (4.71)$$

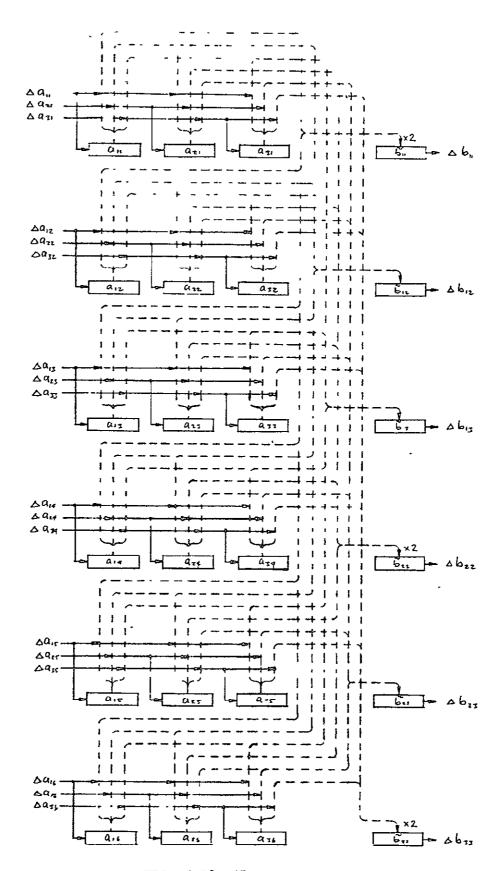


FIG. 4-12 AB computer.

The ΔC computer, described in paragraph h.3.5, requires that all elements of B have the same scale factor. Therefore, let $K_{b} = K_{b}$ for all i and j. The result is that K_{b} must equal $K_{b}/2$, which may be accomplished either by adding twice to the b_{ii} registers for each Δa_{ij} or by delaying the additions by one bit, thus doubling the number added to the register.

In order to ensure that, at most, one Δb_{ij} pulse is produced during each computation cycle, the following constraint is placed on K_a :

$$K_{a \ K=1}^{c} \max \left| a_{ik} \right| + \max \left| a_{jk} \right| \le c \text{ for all i, j} . \tag{4.72}$$

This constraint limits K_a to a lower value than the constraint given by equation (4.71). Since $K_{a_{ij}} = K_a$ for all i and j and since it is reasonable to let $K_{\sigma_j} = K_{\sigma}$ for all j (all wheels have the same speed), equation (4.58) indicates that $K_{\rho_{ij}} = K_{\rho}$ for all 1 and j. Equation (4.58) is therefore replaced with .

$$K_{a} = \frac{K_{\rho}K_{\sigma}}{c} \qquad (4.73)$$

Table 4.4 shows a computation sequence for the additions to the \tilde{b}_{ij} registers where the variables a_{ij} are stored serially on a single circulating register in the order shown. Each \tilde{b}_{ij} register recycles in the period of a one-word interval of the A register. During interval 1, twice the number in the A register during that interval is added to the \tilde{b}_{11} register if $\Delta a_{11} = 1$. The A register also adds to the \tilde{b}_{12} register if $\Delta a_{21} = 1$ during this interval, and to the \tilde{b}_{13} register if $\Delta a_{31} = 1$. All the computations of the ΔB computer are completed in one cycle of the A register.

TABLE 4.4 $\widetilde{\mathbf{B}}$ Computation Sequence

Interval	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1.0	T
A	n ₁₁	a21,	*31	a 12	R ₂₂	a ₃₂	a ₁₃	u ⁵³	a ₃₃	a ₁₄	a ₂₁ +	n ₃₁	a ₁₅	 	15 a ₃₅	16 a ₁₆	17	18
b ₁₁	24 411			24 ⁴ a ₁₂			2A/ a ₁₃			2Ar a ₁₄		34	2A a ₁₅	a ₂₅	35	2A. a ₁₆	a ₂₆	⁸ 30
ñ ₁₂	۸ a ₂₁	M a ₁₁		Aca ₂₂	A a 12		Ar a ₂₃	A4a13		Aca ₂₄	A^a14		Aa25	A a ₁₅		A: a ₂₆	A a ₁₆	
6 13	1-a32		ACR.11	AA 432		ا ادماء	A6 a 33		ΛΔ8 ₁₃	^∧a _{2t}		ννα ¹¹ *	ALa ₃₅		٨.015	^~a ₃₆	-	A-a ₁₆
~ b ₂₂		2 AA 0 21			2 A 4 a 22			2860 ₂₃			246a ₂₄		,	2Aca ₂₅		J .	21ia ₂₆	1 20
° ⁰23		Ма ₃₁	^{Ma} 21		Ana ₃₂	A ∆a ₂₂		ΛΔα ₃₃	Ma23		Ana 34	Asa ₂₄		A-035	£ a ₂₅		At a 36	Ar a ₂₆
ъ 33			21.a31			2A 632			2AL-833		•	240a314			2A a ₃₅		30	21-a ₃₆

4.3.5 AC Computation

The ΔC computer, illustrated in Figure 4.13. computes increments for the adjoint of the B matrix given by equations (4.46). As in the ΔB computer, when squaring computation is performed, the addition to an R register is doubled. This can be accomplished by delaying the number to be added by one bit time. The doubled addition is signified in the figure by a "2" placed next to the ΔX arrowhead which indicates addition of Y to R. As for the previous computers, the scale factors must satisfy

$$K_{c} = \frac{K_{b}^{2}}{c} \qquad (4.74)$$

By requiring that

$$K_{b} \sum \max |b_{i,j}| \le e \tag{4.75}$$

where the summation is taken over the four terms b_{ij} of each of equations (4.46). only one Δc pulse will be produced during each computation cycle.

Table 4.5 presents a computation sequence for the additions to the c registers for this computation, where the elements of B are stored serially on a single circulating register in the sequence shown.

TABLE 4.5
C and d Computation Sequences

Interval:	1	2	3	4	5	6
В:	bll	b ₁₂	^b 13	ъ ₂₂	^b 23	^b 33
e ₁₁				^{ВДЪ} 33	-2B∆b ₂₃	^{B∆b} 22
° 12		- ^{B∆b} 33	^{В∆ъ} 23		^{BΔb} 13	- ^{B∆b} 12
°c ₁₃		^{B∆b} 23	-B∆b ₂₂	-BΔb ₁₃	^{BΔb} 12	
~ €22	^{B∆b} 33		-2B∆b ₁₃			B∆b _{ll}
°c ₂₃	- ^{B∆b} 23	^{B∆b} 13	^{B∆b} 12		-B∆b _{ll}	
°33	B∆b ₂₂	-2BAb _{l2}	^{B∆b} ll			
C:	c ₂₂	°23	°33	cll	c ₁₂	°13
ã₀:	BAc	B∆c ₁₂	_{ВДс} 13	C∆b _{ll}	c∆b _{l2}	_{СФр} 13

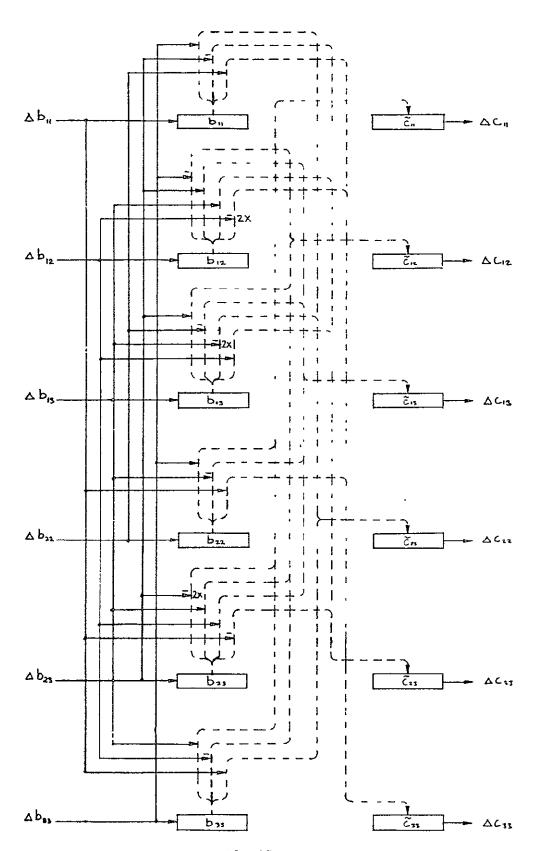


FIG. 4-13 ΔC computer.

4.3.6 Δd_O Computation

Computation of the increments for d_0 , the determinant at the B matrix [equation (4.47)] is performed by adding elements of B and C to a single R register, as shown in Figure 4-14. The sequence of these additions is shown in Table 4.5, where the elements of C are stored on a single register in the sequence shown. The scale factor for d_0 is given by

$$K_{\tilde{G}_{O}} = \frac{K_{\tilde{b}}K_{\tilde{C}}}{c} \tag{4.76}$$

and by constraining $\mathbf{K}_{\mathbf{b}}$ and $\mathbf{K}_{\mathbf{c}}$ so that

$$K_{\mathbf{b}}K_{\mathbf{c}} \sum_{\mathbf{j}=1}^{3} \max |\mathbf{b}_{\mathbf{j}}| + \max |\mathbf{c}_{\mathbf{j}}| \leq c$$
 (4.77)

with only one $\Delta d_{_{\rm O}}$ pulse produced during each computation cycle.

4.3.7 AD Computation

Figure 4-15 illustrates computation of the increments for the 18 D elements given by equations (4 48). Similarly to the previous computers, the scale factors for the elements of D must satisfy

$$K_{d_{i,j}} = \frac{K_a K_c}{c} = K_d$$
 (4.78)

Therefore, they must all be equal. By requiring that

$$K_{a}K_{c} = \sum_{k=1}^{3} \max |a_{ki}| + \max |a_{kj}| \le c \quad \text{for all 1, j}$$
 (4.79)

only one Ad pulse is produced during each computation cycle.

Table 4.6 presents a computation sequence for additions to the \tilde{d} registers where the elements of A and C are stored serially on respective single registers in the relative sequence shown.

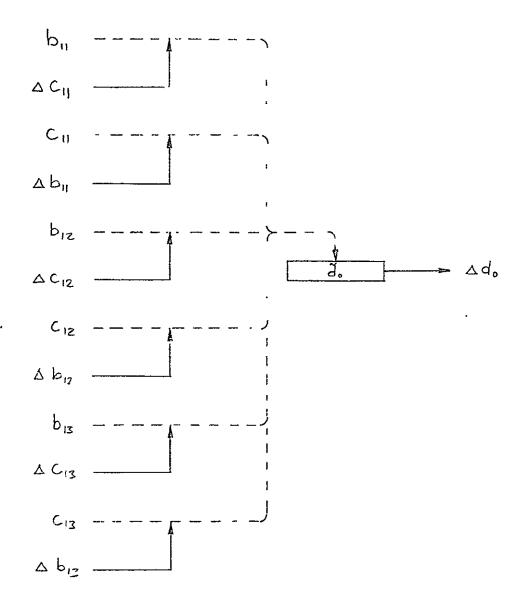


FIG. 4-14 Δd_0 computer.

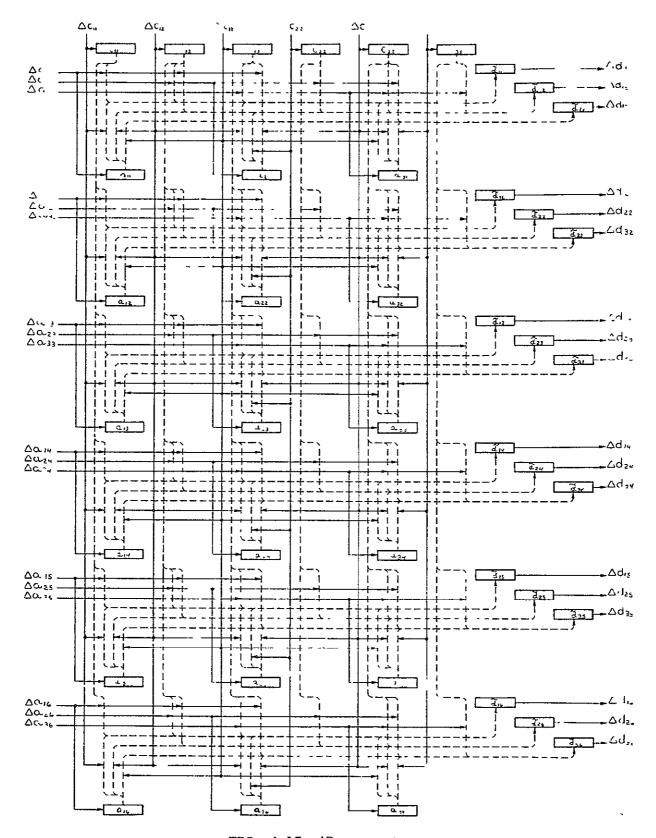


FIG. 4-15 AD computer.

TABLE 4.6

Computation Sequence

Interval:	1	2	3	14	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Å:	*11	a ₂₁	±31	12	*22	4 32	*13	a ₂₃	*33	a ₁₁₊	a ₂₁₊	a ₃₄	a ₁₅	a ₂₅	a ₃₅	a ₁₆	a ₂₆	a ₃₆
Cz	¢11	°12	c13	e ₂₂	c ₂₃	°33	c ₁₁	c ₁₂	c ₁₃	c ₂₂	c ₂₃	c33	e ₁₁	e ₁₂	°13	e ₂₂	c ₂₃	c33
ã ₁₁	10c11	1 ∧c12	41e13				C4e11		-	 		- 55			<u> </u>		13	33
ã ₁₂	10c12	1 ∆c ₂₂	. A∆c23]		C4a ₁₁	l .	C∆a ₂₁	CA231							
ā ₁₃	Mc13	#∆e ₂₃	4∆c ₃₃					•	CA&11	1	CΔ8 ₂₁							
ã ₂₁				We ¹¹	Wc12	13c13	C∆a ₁₂	CAa22	i	l .	İ							
ã ₂₂				10c12	12c22	1	1	C4812		Caa ₂₂	CAA32							
ã ₂₃				™ c13	77°23	A≏e33			C44 ₁₂	ı	Cra ²²	1						
ã ₃₁							1	12°12		1			CAB ₁₃	C∆a23	CAB 33			
ã₃₂							Mc12	Mc ₂₂	₩c ₂₃					CAA13	1	Caa23	C1833	
₹ ₃₃							10c13	^{1∆e} 23	A^e33						Caa ₁₃	1	C1823	
\widetilde{d}_{41}										12¢11	™ c12	ж с ₁₃	C78 ³ 7	ĉv¤ ^S r⁴		1		
ã ₄₂										1∆C ₁₂	Wc ⁵⁵		t	Caa ₁₄	ľ	C=B21	C.=34	
ã₁₄3										17c13	™c23	43e33			C781#	1	C1824	1
ã ₅₁	C7812	C4825	C0a35										11°	12°12			[i	
ã ₅₂		C4a15		C1825	C^a35								Mc12	l .	17.0 ⁵³			
ã ₅₃			C&*15		C4= 25	C4835							۸۵e ₁₃	l	1			
ã ₆₁	Caa ₁₆	C4a ₂₆	^{Ç∆a} 36												•	We ¹¹	12عدم	V76 ¹³
ã ₆₂		C∆a ₁₆		C4a26	C3a36											Mc ₁₂		We ⁵³
ã ₆₃			C4m ₁₆			COB36										776 ¹³		i i

4.3.8 <u>Au Computation</u>

The Au computer performs the divisions of equations (4.49) by multiplications in the feedback paths, as illustrated in Figure 4-16.

When the number stored in the $\tilde{\epsilon}_1$ register is positive, the element identified by the letter S in the figure (and inappropriately but conventionally termed a "servo"), produces positive Δu pulses at the computation cycle rate. When $\tilde{\epsilon}_1$ is negative, the servo produces negative Δu pulses. No pulses are produced when $\tilde{\epsilon}_1$ is zero.

When a positive $\Delta\omega_{\rm cx}$ pulse occurs, the number ${\rm K}_{\rm I_{\rm X}}$ ${\rm I}_{\rm X}$, which is scaled to be nearly as large as c, is added to the ${\rm \widetilde{\epsilon}_1}$ register. Similarly, a positive $\Delta {\rm d}_{\rm o}$ pulse causes ${\rm K}_{\rm u}{\rm u}_1$ to be added to ${\rm \widetilde{\epsilon}_1}$. The resulting $\Delta {\rm u}_1$ pulses produced cause ${\rm K}_{\rm d}{\rm o}_{\rm o}$ to be repeatedly subtracted from ${\rm \widetilde{\epsilon}_1}$ until ${\rm \widetilde{\epsilon}_1}$ is zero. (The register may not go to zero exactly, in which case the servo will generate alternate positive and negative pulses.)

The change in $\tilde{\epsilon}_1$ due to $\Delta \dot{\omega}_{ex}$ pulses or Δd_0 pulses can be expressed as

$$\Delta \varepsilon_{1} = K_{I_{x}} I_{x} \Delta \dot{\omega}_{cx} - K_{u} u_{1} \Delta d_{0} - K_{d_{0}} d_{0} \Delta u_{1}$$
(4.80)

$$= \Delta \left[\begin{pmatrix} K_{\mathbf{I}_{\mathbf{X}}} \mathbf{I}_{\mathbf{X}} \end{pmatrix} \quad \begin{pmatrix} K_{\dot{\mathbf{w}}_{\mathbf{X}}} \dot{\dot{\mathbf{w}}}_{\mathbf{C}\mathbf{X}} \end{pmatrix} \right] - \Delta \left[\begin{pmatrix} K_{\mathbf{u}} \mathbf{u}_{\mathbf{I}} \end{pmatrix} \quad \begin{pmatrix} K_{\mathbf{d}_{\mathbf{O}}} \mathbf{d}_{\mathbf{O}} \end{pmatrix} \right]. \tag{4.81}$$

Since $\tilde{\epsilon}_1 \approx 0$, and with proper initialization of the d_0 and u_1 registers,

$$u_1 \approx \frac{K_1 K_{\omega_x}}{K_u K_{d_0}} = \frac{I_x \hat{\omega}_{cx}}{d_0} . \qquad (4.82)$$

To satisfy equations (4.49), the scale factors must therefore satisfy

$$\frac{K_{\mathbf{I}_{\mathbf{X}}}K_{\mathbf{w}_{\mathbf{X}}}^{\bullet}}{K_{\mathbf{u}}K_{\mathbf{d}_{\mathbf{Q}}}} = 1 \qquad . \tag{4.83}$$

Similar requirements apply to the y and z axes.

To ensure that the ϵ_1 register does not overflow, the scale factors should also satisfy

$$K_{I_{x}}I_{x} + K_{u} \max \left| u_{1} \right| + K_{d_{0}} \max \left| d_{0} \right| \leq c$$
 (4.84)

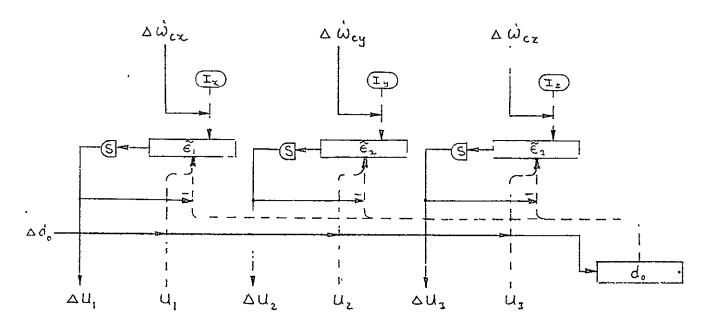


FIG. 4-16 Δu computer.

Table 4.7 presents a computation sequence for $\tilde{\epsilon}_1$, $\tilde{\epsilon}_2$, and $\tilde{\epsilon}_3$, where u_1 , u_2 , and u_3 are stored serially on a single register as shown, and where d_0 is stored on a single register that recycles at the rate of each element of u. The computation is completed in two cycles of the u register.

TABLE 4.7 © Computation Sequence

Interval:	1	2	3	4	5	6
u:	ul	u ₂	u ₃	ul	^u 2	^u 3
d _o :	^đ o	d _o	d _o	d _o	d _o	d _o
<u>ء</u> 1	u∆d _o			^đ o ^{∆u} l		
≈ 2		u∆đ _o			d _o ∆u ₂	
≈ [€] 3·			u∆đ _o			d _o ∆u ₃

1 4.3.9 1 2 Computation

The $\Delta\dot{a}_c$ computer, illustrated in Figure 4-17, computes increments for the desired outputs of the steering law computer [equations (4.50)]. As in the previous cases, the scale factor for the registers that accumulate the $\Delta\dot{a}_c$ pulses (not shown) must satisfy

$$K_{\alpha} = \frac{K_{\bar{d}}K_{u}}{c} \quad . \tag{4.85}$$

By requiring that

$$K_{\alpha} \stackrel{3}{\underset{i=1}{\Sigma}} \max \left| d_{ij} \right| + \max \left| u_{j} \right| \leq c \text{ for each 1}$$
 (4.86)

only one $\tilde{\alpha}_{\mathbf{c}}$ register overflow can occur during each computation cycle.

Table 4.8 shows a computation sequence for the $\overset{\circ}{\alpha}_c$ registers, where the elements of D and u are each stored serially on single long registers in the sequence shown.

Since $\dot{a}_{\rm c}$ is most likely desired in analog form for the CMG gimbal control system, the $\Delta \dot{a}_{\rm c}$ pulses may be fed into counters that are parts of a D/A conversion system.

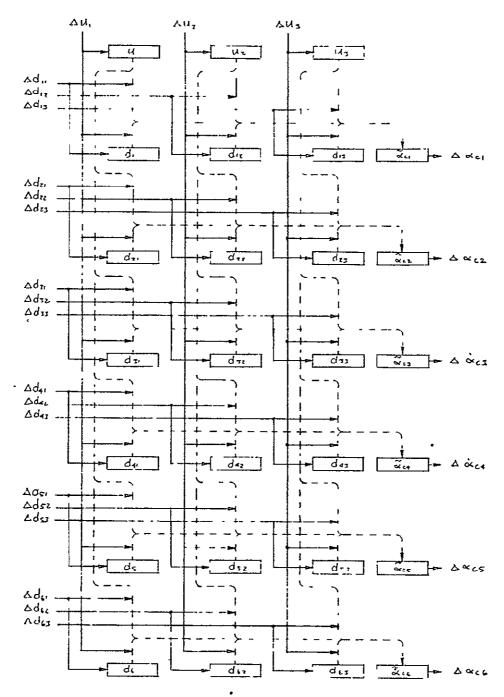


FIG. 4-17 $\Delta \alpha_{c}$ computer.

- 80 -

TABLE 4.8

Interval:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
D:	_q 11	d ₁₂	d ₁₃	^d 21	d ₂₂	^d 23	d31	d32	a ₃₃	d ₁₊₁	d142	d1+3	^d 51	d52	₫53	^d 61	d ₆₂	d ₆₃
u;	u ₁	u ₂	^u 3	^u l	u ₂	^u 3	ul	^ц 2	uз	u ₁	u ₂	^u 3	ul	u ₂	u ₃	u ₁	u ₂	^u 3
ã₀1	DΔu ₂	D∆u ₂	^{D∆u} 3	uad _{ll}	^{иΔđ} 12	u∆d ₁₃												
~ ac2		ս∆մ ₂₂	u∆d ₂₃	DΔu _l	D∆u ₂	^{D∆u} 3	u∆d ₂₁											
~ α°ο3			u∆d ₃₃	u∆d ₃₁	u∆d ₃₂	'	^{D∆u} 1	D∆u ₂	^{D∆u} 3									
~ åc⁴				usd _{h1}	u∆D _{l+2}	u∆d ₁₄₃				DAul	DAu ₂	DAu3					}	<u> </u>
~ α _{c5}					^{u∆d} 52	u∆d ₅₃	u∆d ₅₁						^{D∆} u ₁	D∆u ₂	^{D∆u} 3			
~ °c6				;		u∆d ₆₃	u∆d ₆₁	u∆d ₆₂								D∆u _l	D∆u ₂	D∆u ₃

4.4 OTHER COMPUTATIONS

4.4.1 Triad Conversion

The triad converter changes the six rate signals $r_s = \{r_{s1}, \cdots, r_{s6}\}$ from the dodecahedron configured rate gyros, described in paragraph 4.2.3, to vehicle rates $\omega_s = \{\omega_{sx}, \omega_{sy}, \omega_{sz}\}$. The equations to be computed are given by equations (4.21) and (4.22) and are repeated here for convenience:

$$\omega_{s} = E^{\dagger} r_{s}$$

where

$$E^{\dagger} = (E^{T}E)^{-1} E^{T}$$

$$E = \lambda \overline{E}$$

$$\lambda = \text{diag} \left\{ \lambda_1, \ldots, \lambda_6 \right\}$$

$$s = \sin \delta \approx 0.526$$
.

$$c = \cos \delta \approx 0.850$$

If rate gyro number 1 is used, $\lambda_{1}=1$; if it is switched off because it has failed, $\lambda_{1}=0$. Let

$$F = E^{T}E \tag{4.87}$$

$$P = adj F (4.88)$$

$$Q = PE^{T}$$
 (4.89)

$$q_O = \det F$$
 . (4.90)

Then

$$\omega_{\rm S} = \frac{1}{\rm q_0} \, Qr_{\rm S} \quad . \tag{4.91}$$

Since E changes with λ , the Q matrix can be recomputed by performing these computations each time λ changes. This method requires minimum memory and is probably the preferred method with a general purpose computer. The elements of Q can also be expressed in terms of the elements of λ . This method is preferred for incremental and analog computation, and is described as follows. Let

$$\mu_1 = 2s^{\frac{1}{2}}c$$
 (4.92)

$$\mu_2 = 2s^5 + \mu_1$$
 (4.93)

$$\mu_3 = \mu_1 + \mu_2$$
 (4.94)

$$\mu_{14} = \mu_{2} + \mu_{3} \tag{4.95}$$

$$\lambda_{1,jk} = \lambda_{1}\lambda_{j}\lambda_{k}. \tag{4.96}$$

Then the 18 elements of Q are given by the following expressions:

$$q_{11} = \frac{1}{12}\lambda_{123} + \frac{\mu_{2}\lambda_{124} + \mu_{4}\lambda_{125}}{\mu_{4}\lambda_{135} - \mu_{1}\lambda_{136}}$$

$$+\frac{\mu_{4}\lambda_{126} + \mu_{2}\lambda_{135} - \mu_{1}\lambda_{136}}{\mu_{1}\lambda_{145} + \mu_{2}\lambda_{146} + 2\mu_{2}\lambda_{156}}$$

$$q_{12} = -\frac{\mu_{2}\lambda_{123} - \mu_{2}\lambda_{124} - \mu_{4}\lambda_{125}}{\mu_{4}\lambda_{126} + \mu_{1}\lambda_{235} - \mu_{2}\lambda_{236}}$$

$$-\frac{\mu_{4}\lambda_{126} + \mu_{1}\lambda_{235} - \mu_{2}\lambda_{236}}{\mu_{2}\lambda_{256} + \mu_{1}\lambda_{246} + 2\mu_{2}\lambda_{256}}$$

$$q_{13} = \frac{\mu_{3}\lambda_{134} + \mu_{4}\lambda_{135} + \mu_{3}\lambda_{136}}{\mu_{3}\lambda_{234} + \mu_{3}\lambda_{235} + \mu_{4}\lambda_{236}}$$

$$+\frac{\mu_{1}\lambda_{346} + \mu_{1}\lambda_{346} + 2\mu_{3}\lambda_{356}}{\mu_{14} = \mu_{3}\lambda_{134} + \mu_{3}\lambda_{145} + \mu_{4}\lambda_{146}}$$

$$+\frac{\mu_{1}\lambda_{345} + \mu_{1}\lambda_{245} + \mu_{3}\lambda_{246}}{\mu_{1}\lambda_{345} + \mu_{1}\lambda_{346} + 2\mu_{3}\lambda_{456}}$$

$$+\frac{\mu_{1}\lambda_{345} + \mu_{1}\lambda_{346} + 2\mu_{3}\lambda_{456}}{\mu_{1}\lambda_{345} + \mu_{1}\lambda_{346} + 2\mu_{3}\lambda_{456}}$$

$$q_{15} = -\mu_3 \lambda_{135} + \mu_2 \lambda_{145} - \mu_3 \lambda_{156}$$

$$-\mu_2 \lambda_{235} + \mu_3 \lambda_{245} + \mu_3 \lambda_{256}$$

$$-\mu_2 \lambda_{356} + \mu_2 \lambda_{456}$$

$$q_{16} = -\mu_2 \lambda_{136} + \mu_3 \lambda_{146} + \mu_3 \lambda_{156}$$

$$-\mu_3 \lambda_{236} + \mu_2 \lambda_{246} - \mu_3 \lambda_{256}$$

$$-\mu_2 \lambda_{356} + \mu_2 \lambda_{456}$$

$$q_{21} = -\mu_3 \lambda_{123} + \mu_3 \lambda_{124} - \mu_2 \lambda_{125}$$

$$+\mu_2 \lambda_{126} - \mu_3 \lambda_{135} + \mu_2 \lambda_{135}$$

$$-\mu_2 \lambda_{145} + \mu_3 \lambda_{146}$$

$$q_{22} = \mu_3 \lambda_{123} - \mu_3 \lambda_{124} - \mu_2 \lambda_{125}$$

$$+\mu_2 \lambda_{126} - \mu_2 \lambda_{235} + \mu_3 \lambda_{236}$$

$$-\mu_3 \lambda_{245} + \mu_2 \lambda_{246}$$

$$q_{23} = 2\mu_2 \lambda_{123} + \mu_4 \lambda_{134} + \mu_2 \lambda_{135}$$

$$-\mu_1 \lambda_{136} + \mu_4 \lambda_{234} - \mu_1 \lambda_{235}$$

$$+\mu_2 \lambda_{236} + \mu_2 \lambda_{345} + \mu_2 \lambda_{346}$$

$$q_{24} = -2\mu_2 \lambda_{124} - \mu_4 \lambda_{134} - \mu_1 \lambda_{145}$$

$$-\mu_2 \lambda_{146} - \mu_4 \lambda_{234} - \mu_2 \lambda_{245}$$

$$+\mu_1 \lambda_{246} - \mu_2 \lambda_{345} - \mu_2 \lambda_{346}$$

$$q_{25} = 2\mu_3 \lambda_{125} + \mu_4 \lambda_{135} + \mu_3 \lambda_{145}$$

$$+\mu_1 \lambda_{156} + \mu_3 \lambda_{235} + \mu_4 \lambda_{245}$$

$$+\mu_1 \lambda_{156} + \mu_3 \lambda_{235} + \mu_4 \lambda_{245}$$

$$+\mu_1 \lambda_{156} + \mu_3 \lambda_{235} + \mu_4 \lambda_{245}$$

$$+\mu_1 \lambda_{256} + \mu_3 \lambda_{356} + \mu_3 \lambda_{456}$$

$$q_{26} = 2\mu_{3}\lambda_{126} + \mu_{3}\lambda_{136} + \mu_{4}\lambda_{146}$$

$$+\mu_{3}\lambda_{156} + \mu_{4}\lambda_{236} + \mu_{3}\lambda_{246}$$

$$+\mu_{1}\lambda_{256} + \mu_{3}\lambda_{356} + \mu_{3}\lambda_{456}$$

$$q_{31} = \mu_{1}\lambda_{123} + \mu_{1}\lambda_{124} + \mu_{3}\lambda_{135}$$

$$+\mu_{3}\lambda_{126} + 2\mu_{3}\lambda_{134} + \mu_{4}\lambda_{135}$$

$$-\mu_{3}\lambda_{136} + \mu_{3}\lambda_{145} + \mu_{4}\lambda_{146}$$

$$q_{32} = \mu_{1}\lambda_{123} + \mu_{1}\lambda_{124} + \mu_{3}\lambda_{125}$$

$$+\mu_{3}\lambda_{126} + 2\mu_{3}\lambda_{234} + \mu_{3}\lambda_{235}$$

$$+\mu_{4}\lambda_{236} + \mu_{4}\lambda_{245} + \mu_{3}\lambda_{246}$$

$$q_{33} = -\mu_{2}\lambda_{134} - \mu_{3}\lambda_{135} - \mu_{2}\lambda_{136}$$

$$+\mu_{2}\lambda_{234} + \mu_{2}\lambda_{235} + \mu_{3}\lambda_{236}$$

$$-\mu_{3}\lambda_{345} + \mu_{3}\lambda_{346}$$

$$q_{34} = -\mu_{2}\lambda_{134} - \mu_{2}\lambda_{145} - \mu_{3}\lambda_{146}$$

$$+\mu_{2}\lambda_{234} + \mu_{3}\lambda_{245} + \mu_{2}\lambda_{246}$$

$$+\mu_{3}\lambda_{345} - \mu_{3}\lambda_{346}$$

$$q_{35} = \mu_{2}\lambda_{135} - \mu_{1}\lambda_{145} + \mu_{2}\lambda_{256}$$

$$+\mu_{1}\lambda_{235} + \mu_{2}\lambda_{245} + \mu_{2}\lambda_{256}$$

$$+2\mu_{2}\lambda_{345} + \mu_{4}\lambda_{356} + \mu_{4}\lambda_{456}$$

$$q_{36} = \mu_{1}\lambda_{136} - \mu_{2}\lambda_{146} - \mu_{2}\lambda_{256}$$

$$-\mu_{2}\lambda_{236} + \mu_{1}\lambda_{246} - \mu_{2}\lambda_{256}$$

To express q in a similar manner, let

$$\mu_5 = \dot{\mu}_5^{\mu} c^2 = (c^3 - s^3)^2$$
 (4.98)

$$\mu_6 = \mu_8^2 c^4 = (c^3 + s^3)^2$$
 (4.99)

Then

$$q_{0} = \mu_{5}^{\lambda}_{123} + \mu_{5}^{\lambda}_{124} + \mu_{6}^{\lambda}_{125}$$

$$+ \mu_{6}^{\lambda}_{126} + \mu_{6}^{\lambda}_{134} + \mu_{6}^{\lambda}_{135}$$

$$+ \mu_{5}^{\lambda}_{136} + \mu_{5}^{\lambda}_{145} + \mu_{6}^{\lambda}_{146}$$

$$+ \mu_{5}^{\lambda}_{156} + \mu_{6}^{\lambda}_{234} + \mu_{5}^{\lambda}_{235}$$

$$+ \mu_{6}^{\lambda}_{236} + \mu_{6}^{\lambda}_{245} + \mu_{5}^{\lambda}_{246}$$

$$+ \mu_{5}^{\lambda}_{256} + \mu_{5}^{\lambda}_{345} + \mu_{6}^{\lambda}_{346}$$

$$+ \mu_{6}^{\lambda}_{356} + \mu_{6}^{\lambda}_{456} \cdot$$

$$+ \mu_{6}^{\lambda}_{356} + \mu_{6}^{\lambda}_{456} \cdot$$

All of the preceding elements are sums of the constants $\{\mu_1, \dots, \mu_6\}$ weighted by λ 's that are either one or zero. A possible method for computing ω_s [equation (4.91)] by the incremental method described in paragraph 4.3 is to initially store the 16 q's and the q_o that correspond to no failures in the Y registers; then when a failure occurs, change the q's in accordance with the preceding equations. Only the six constants $\{\mu_1, \dots, \mu_6\}$ need to be stored to accomplish the required changes in the q's and q_o . The incremental computation for αr_s will then be similar to the αr_s and αr_s computations described in paragraph 4.3.

4.4.2 Control Compensation, Failure Monitoring, and Mode Control

The three compensators required for the vehicle rate loop (see Figure 4-6) can readily be accomplished by incremental computation. The application of this computation technique to flight controls, for example, has been studied by several flight control system manufacturers, including Sperry. Due to the limited scope of this study, this section of the CMG control computer will not be investigated.

The failure monitoring and mode control function of the CMG control computer (Figure 4-6) generates the λ 's for the triad conversion; the rotor speeds σ for the steering law computer; and supplies the display signals required to monitor the failure status of the CMG's and sensors. The major computations required for this function are the parity check equations for the sensors listed in Table 4.1. A computer structure for the computations required by the failure monitoring and mode control function is not presented in this study due to its limited scope.

4.5 CONCLUSIONS AND FECOMMENDATIONS FOR FURTHER STUDY

The steering law computations are by far the most complex computations required by a CMG control computer, and they outweigh the remaining computing functions in selecting the type of computer to employ for controlling CMG's. Since these computations are time-variant and nonlinear, digital computation is required. A general purpose computer can certainly perform these computations but it is considerably more limited in speed than an incremental computer. The time required to do the steering law computations on a UNIVAC® 1819 computer (designed for airborne use) is estimated to be 6.37 milliseconds. If we roughly estimate that the time required to perform the total CMG control computer computations is 10 milliseconds, then a sampling rate of 100 samples per second saturates the computer. For some of the anticipated requirements for future CMG control systems, sampling rates of this order are required. It can therefore be concluded that the use of a central, general purpose computer, which is also required to perform other than CMG control functions, is not feasible for the type of CMG system described in this report.

An incremental computer can be made much faster than a general purpose computer, but its speed depends on the level of serialization of its computations. A bit-time of 0.5 microsecond is easily accomplished, and if a 300-bit register is used to serially store a set of 18 Y variables (such as the 18 a's or d's), a computation cycle takes 0.15 millisecond. Of course, there are also lags in incremental computers that must be considered when comparing them with the general purpose type, but it is clear that incremental computers are much faster. Also, since computations are performed in parallel, adding functions to an incremental computer does not require additional computation time.

In terms of complexity, it is not obvious at this stage which type of computer is the simplest. Further study would be required to determine parts counts. They may be quite competitive in this aspect.

Since incremental CMG control computers have some definite advantages over general purpose computers for this application, it is recommended that a further study be initiated to design a prototype incremental computer for a specific CMG control system requirement, and to compare it with a general purpose type, programmed for the same function, in terms of complexity (parts count), accuracy, reliability, weight, and power consumption.

REFERENCES

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- 2 L. A. Zadeh and A. Desoer, <u>Linear System Theory</u>, McGraw-Hill Book Co., Inc, New York, 1963, pp 577 - 582.
- 3 Ralph Deutsch, <u>Estimation Theory</u>, Prentice-Hall Inc, Englewood Cliffs, New Jersey, 1965, pp 82 87.
- 4 J. P. Gilmore, A Non-Orthogonal Multi-Sensor Strapdown Inertial Reference Unit, Instrumentation Laboratory, Massachusetts Institute of Technology, E-2308, August 1968, (NASA Contract NAS 9-8242).
- 5 Ibid.
- 6 Deutsch, p 83.
- 7 <u>Ibid</u>, pp 83 84.

CHAPTER 5

SIMU DIRECTION COSINE SIMULATION PROGRAM RUNS

5.1 DESCRIPTION OF METHOD AND RESULTS

The purpose of the simulation of SIMU operation was to determine the error accumulation for large angle changes in position and also the worst-case mode of error accumulation during extended runs.

5.1.1 Types of Runs

Three types of runs were made and are described below.

- (1) Runs simulating a motion to a given angle and then back to the zero position. The angles used range from less than 1^0 to 180^0 .
- (2) Oscillatory runs taken near the zero reference position where the curve of data from the test above indicates that the worst error accumulation occurs.
- (3) Three-axis rotations where the inputs are: (a) up to one radian for x, followed by one radian for y and then one radian for z, followed in reverse order for the return to zero; (b) single pulse increments in x, y and z followed successively until each axis has had the pulse required to read up to one radian rotation (32,768), then the reverse order of the same increments of x, y and z until zero is reached.

5.1.2 Test Results

The results of these tests show the following:

Figure 5-1 shows that error accumulations in direction cosine values after rotation to a particular angle (of 180° or less) and then returning to zero degrees were limited to a maximum value of approximately one part in 37. Refer also to Table 5.1.

The error moves up steeply until approximately 2000 unidirectional input pulses have been accumulated. This is approximately a range of one bit of error for every two pulses fed the system by the time the rotation back to zero is completed. (See steep initial slope on Fig 5-1.)

The three axis runs were made for continuous inputs of a fixed number of pulses for x, y and then z sequentially. They were also made for runs where the input pulses were increments of Δx , Δy and Δz repeated in that order until the required number of sets of pulses were processed. Thereafter the reverse sequences of pulses were given to return the system to the zero reference. Table 5.2 lists the above data plus that for each set of two axis updates for 8, 128 and 32,768 sets of input pulses, the value 22,768 approximating one radian of rotation. The results show the order of magnitude of error for the number of pulses specified to be the same as for single axis operation. However, as is expected, they are not identical values.

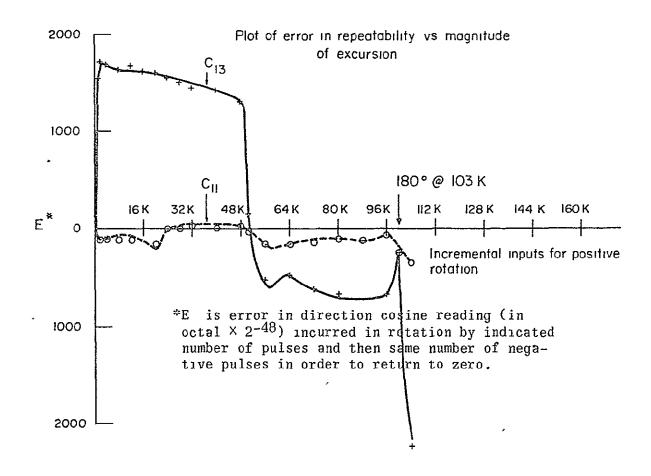


FIG. 5-1 Plot of error in repeatability.

The oscillatory runs consisted of ten cycles from 0 to 1024 pulses and back to determine the effect of extended testing on the maximum error rate that the system initially produced. (See Fig. 5-1.) The result was that the error increased proportionally for as many input pulses as were applied. See Table 5.3

These tests were run to provide a reference to determine the correct operation of the SIMU.

TABLE 5.1
SIMU Simulation Data

Single Axis Values After n(\Delta\theta) Pulses

<u> </u>		C11		C13					
1.024	037770	000052	165024	000777	165253	027743			
2.048	037740	001252	151642	001777	052536	017055			
4.096	037600	025245	035227	003772	125673	160345			
8.192	037002	124477	036241	007725	073552	133023			
32.768	021224	050037	135327	032732	124436	043614			
106,496	140140	026754	104267	174423	052267	067173			

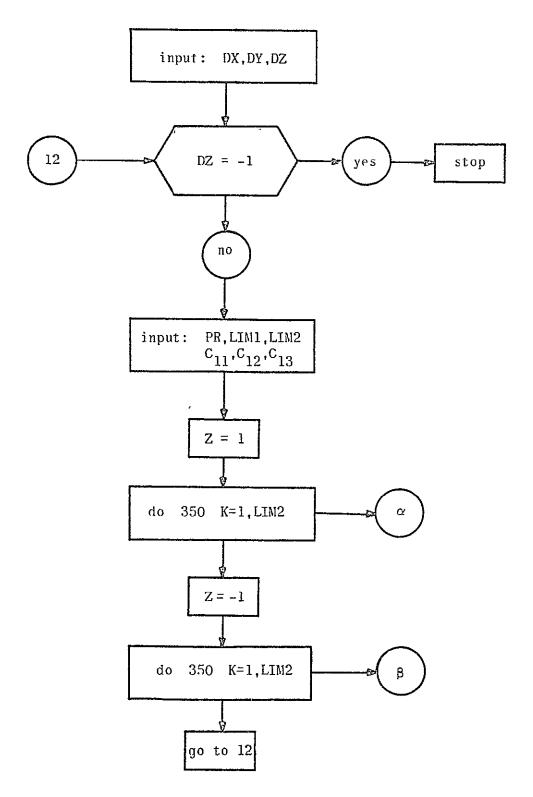
Single Axis Return to Zero Values After n(Δθ) Pulses and n(-Δθ)

<u>n</u>		C11		C13				
1.024	040000	000000	037670	000000	000000	041541		
2.048	040000	000000	037666	000000	000000	041727		
4.096	040000	000000	037675	000000	000000	041706		
8.192	040000	000000	037675	000000	000000	041662		
12,288	040000	000000	037663	000000	000000	041651		
16.384	040000	000000	037711	000000	000000	041622		
32,768	040000	000000	040031	000000	000000	041461		
65.536	040000	000000	037631	000000	000000	037303		
98,304	040000	000000	037717	000000	000000	037112		
106,496	040000	000000	037444	000000	000000	035560		

5.2 PROGRAM DESCRIPTION

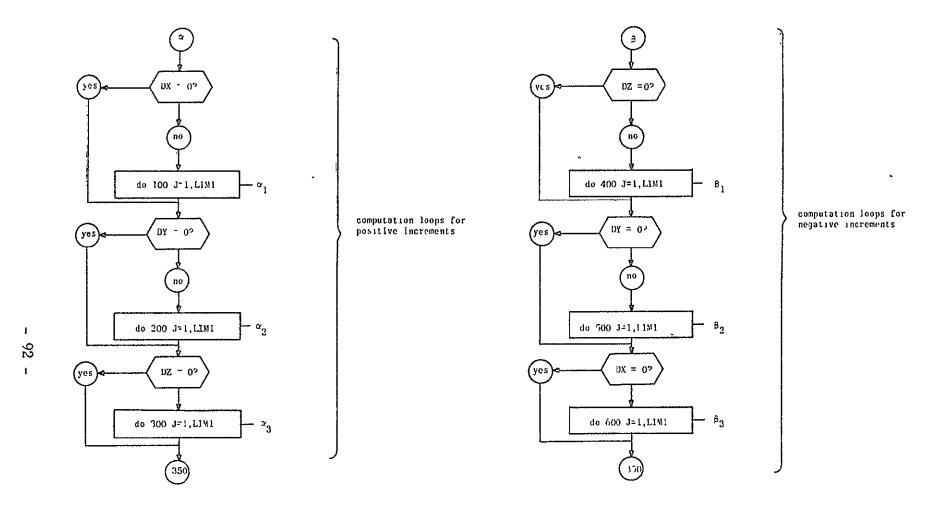
The program, written for the UNIVAC 1108 in Fortran IV, computes new direction cosines from old direction cosines using the truncation-error-free algorithm. See the flow chart (Fig. 5-2) to determine how this simulation was programmed.

The nature of the iterative process is controlled by punched card inputs in the format described below. Provision was made for controlling iteration by selecting angular increments in each of the three axial senses, \vec{x} , \vec{y} and \vec{z} . Let the three selection variables be DX, DY, DZ. DX=0 means skip an angular increment in this sense. DX \neq 0 means perform the appropriate iteration for an angular increment in this sense (this angular increment is assumed fixed). Refer to Fig. 5-3.



Input and Control Initialization

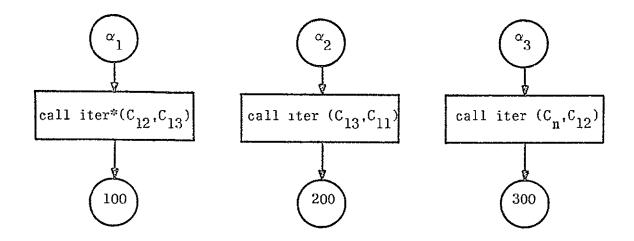
FIG. 5-2 Flow charts of simulation program.



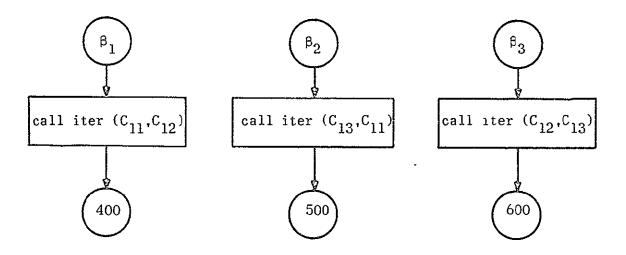
Choice of Angular Increment

Choice of Angular Increment

FIG. 5-2 Flow charts of simulation program (cont.).



computation for positive increments



computation for negative increments

*ITER is the subroutine that actually performs the computation on the pair of direction cosines that are the arguments in the call statement.

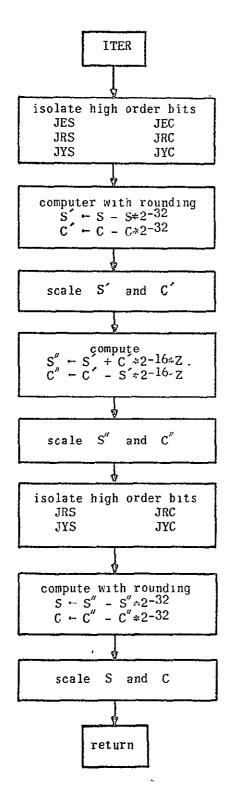
ITER itself calls another routine SCALE which scales the 3 integer variables of each C $_{i\,J}$ to lie within 0 and 2^{16} - 1 :

The variable Z is set to +1 for positive increments and -1 for negative increments.

Printing is done after each call to iter depending on the control - variable PR.

Computation for New Direction Cosines

FIG. 5-2 Flow charts of simulation program (cont.).



arguments: (S,C)

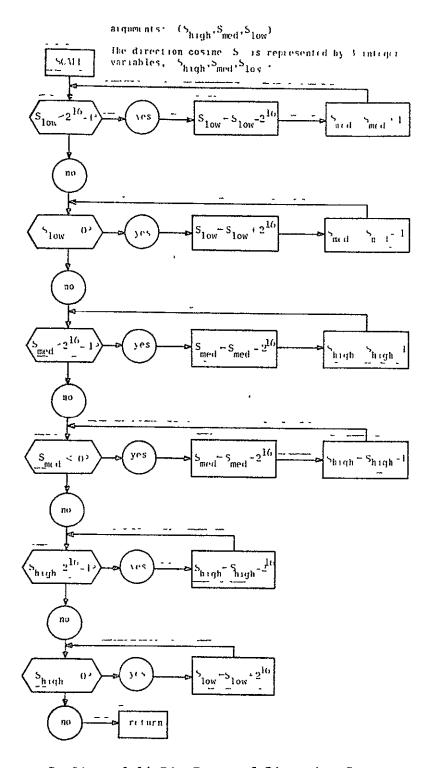
*S represents the three integer variables holding the three 16-bit parts of the 1st direction cosine, and C is used to represent the 2nd. JFS, JEC, etc., represent corresponding high order bits for each part.

Computation is achieved by adding or subtracting the parts of $S.C.S-2^{-32}$, $C*2^{-32}$, etc., that are of corresponding order. The high order bits are used to perform rounding and "shifting". See program for details.

S',C',S'',C'' represent intermediary results which are in the same format as S and C.

Actual Computation of New Direction Cosines

FIG. 5-2 Flow charts of simulation program (cont.).



Scaling of 16-Bit Parts of Direction Cosine

FIG. 5-2 Flow charts of simulation program (cont.).

Two further variables, LIM1 and LIM2, control the length of the iterative procedure. Two specific settings of LIM1 and LIM2 are of interest:

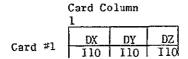
- (1) LIM1=1, LIM2=K means iterate K times in the first selected axial sense, then K times in the second, etc.
- (2) LIM1=K, LIM2=1 means perform K times the sequence {one iteration in the first selected sense, followed by one iteration in the second selected sense} etc.

The program performs the "mirror-image" of the iteration sequence in order to return to the starting point.

One further variable, PR, is provided to control print frequency. If PR=K, then each N^{th} iteration in any selected axial sense forces output of all the direction cosines.

Input variables C11, C12, C13 are provided to enable the user to specify different initial direction cosines. C11, C12, C13 are always entered and printed out as 6 digit octal numbers.

The program performs only integer arithmetic, using one Fortran integer variable to hold the three 16-bit parts of each 48-bit $C_{\text{T},\text{I}}$, as well as intermediary results (see Table 5.4).



IlO = integer, field width of 10

C 3		PR	LIM1	LIM2
Card	#-2	110	I10	I10

	high order 16 bits	medium order 16 bits	low order 16 bits
Card #3-5	c _{1,j}	c _{ij}	c _{i,l}
	θF	θF	€ F

Cll on Card 3 Cl2 on Card 4

 $\theta F = octal$ integer, field width of F

Cand 6	DX'	DY ´	DZ '
Card 6	I10	110	110

At the end of a sequence specified by one set of data, the program reads a new DX', DY', DZ'. If DX'=-1 the program stops, otherwise, computation resumes with a new set of data which is assumed to follow card 6, etc.

FIG. 5-3 Card input format.

C	1	a							
1	1	Q		_					
٥		բերգեր	U4883F	2253-1	600005	ยงกรอบ	Dacher	อดมายถ	- 40 CG-
1	ידדדי	177777	140000	חררססט	320000	J43000	ინიიიი	19300	ידדדיי
7	י לבבל ב	177775	040000	ลออกกก	100000	740000	000001	202021	r オフフフ4
3	~37777	177773	140000	300000	อดอดอล	247088	066671	100006	C 37765
4	~ 37777	177770	849096	l poposon	<u> ը</u> ըըըը,	046000	000002	00000	C 1775
a	~37777	177753	146061	00037n	500000	240606	000002	10076	C 27777
t	77777	177758	[40000	100360	בכספרם	เ ษาเกธ	737030	ממירונ	C 376f4
7	£77777	177747	140336	Locard	SEDEDE	640000	268807	100000	737611
3	777777	177745	840006	200000	000000	647668	000004	000000	r ₹752~
- 1	737777	177747	14055r	000000	ccoone	640000	688663	17000	C 3761 ~
-2	ללללבט	177756	1,40000	1. CETALE	000000	047780	0.0007	002700	r 77567
- 3	77777	177763	140006	Carunn	reacur	047006	600002	10000-	~ 7772~
- 4	2666	17777	5#03C1	J\$75.7	050001	647790	202072	prance	~37744
- 5	יקודיז	177777	146000	Locaur	10000°	845001	000071	10008	c 3775°
-:	דקיקיי	.77776	04706r	000000	, ceacar	040000	000001	profes	237765
- 7	~ ~ 7 7 7 7	177777	148337	60000n	acanar	040000	000061	102201	7777
- 5	იციევი	20[10r	[482]ი	500000	~ueco	047700	000000	enches	F ~7777 ~

Single axis - 0 to 8 pulses and return to 0 again.

CYC:1

PR:8

SEQ:128,:-128,:0

S:0,:0,:848000

C:040000,:0,:040000

```
8=
            4=
                     g=
                         37520
                                   = 37777= 177740=
   16=
           18=
                     0=
                         35240
                                   =
                                      37777= 177600=
                                                       40000
   24=
           1 4⇒
                     Ø=
                         26760
                                      37777= 177340=
                                                       40000
   32≈
           28=
                     0≈
                         12500
                                   æ
                                      37777= 177880=
                                                       40000
   48=
           23= 177777= 166224
                                   =
                                      37777= 176349=
                                                       40003
           27= 177777= 127754
   48=
                                   22
                                      37777= 175600=
                                                       40013
   56=
           33= 177777=
                        55594
                                   EZ
                                      37777= 174740=
                                                       40026
   64=
           37= 177776= 165234
                                   =
                                      37777= 174000=
   72=
           43= 177776=
                         54764
                                      37777= 172740=
                                                       40100
   80=
           47= 177775= 122514
                                      37777= 171600=
                                                       40143
   88=
           53= 177774= 144244
                                      37777= 170340=
                                                       49222
  96=
           57= 177773= 137774
                                      37777= 167000=
                                                       40320
                                  Œ
= 104=
           63= 177772= 103524
                                      37777= 165348=
                                                       40440
= 112=
           67= 177771=
                         15254
                                   =
                                      37777= 163600=
                                                       40605
= 120=
           73= 177767=
                         73884
                                   22
                                      37777= 161740=
                                                       41002
= 128=
           77= 177765= 112534
                                   =
                                      37777= 160000=
                                                       41233
<del>=-</del> 8=
           73= 177767='
                         73014
                                      37777= 161740=
                                                       40777
=- 16=
                                      37777= 163690=
           67= 177771=
                         15274
                                   =
                                                       40576
=- 24=
           63= 177772= 103554
                                      37777= 165340=
                                   E
                                                       40426
=- 32=
           57= 177773= 140034
                                   =
                                      37777= 167000=
                                                       40304
=- 40=
           53= 177774=
                        144314
                                   E
                                      37777= 170340=
                                                       40204
=- 48=
           47= 177775= 122574
                                   #
                                      37777= 171600=
                                                       40123
=- 56=
           43= 177776=
                                      37777= 172740=
                         55054
                                                       49857
=- 64=
           37= 177776=
                        165334
                                      37777= 174000=
                                                       40025
=- 72=
           33= 177777=
                                   ×
                                      37777= [74748=
                         55614
                                                       40003
=- 8Ø≈
           27= 177777=
                        130074
                                   •
                                      37777= 175600=
                                                       37767
=- 88=
           23= 177777= 166354
                                   =
                                      37777= 176340=
                                                       37757
=- 96=
           20=
                     Ø≓
                         12638
                                   ⊭
                                      37777= 177000=
                                                       37753
=-104=
           1 4=
                     Ø=
                         27198
                                   E
                                      37777= 177348=
                                                       37753
=-112=
           10=
                     Ø=
                                   *
                                      37777= 177608=
                         35350
                                                       37753
=- 120=
                                      37777= 177740=
                         37620
                                                       37753
            0=
=-128=
                     Ø≖
                                      40000×
                          40070
                                                   Ø=
                                                       37753
```

Single axis - 0 to 128 pulses and return to 0 again. TABLE 5.2

Results of SIMU Simulation Program for Checkout Runs

CPC:1 PR:4896 SE0:32768,:-32766,:0 S:0,:0,:040000 C:047300,.0,:040000 = 4096= 3772= 125

```
3772= 125673= 160345
                                          = 3760B= 25245=
             7725= 73552= 133723 = 37032= 124477=
13561= 1125= 130127 = 35615= 67727=
17256= 164164= 101440 = 34052= 50014=
= 8192=
                                                                     36241
= 12288=
            13561=
                                                          67727=
                                                                     72357
= 16384= 17256= 164164= 101440
                                                          50014= 175554
            22562= 35725= 43374 = 31746= 159733= 64506
25637= 174055= 132252 = 27323= 176614= 172114
30437= 67319= 46071 = 24406= 13657= 173432
= 20480= 22562= 35725=
= 24576=
= 28672=
                                 43614 = 21224=
46071 = 24406=
= 32768=
             32732= 124436=
                                                          50037= 135327
=- 4096=
             30437= 67310= 46071
                                                          13657= 173433
=- 8192= 25637= 174955= 132221 = 27323= 176614= 172210
                                          = 31746= 150733= 64761
= 34952= 59914= 175747
=-12288=
            22562=
                      35725=
                                 43371
            17256= 164164= 191359
=-16384=
                                         = 35615= 67727=
= 37002= 124477=
=-20480= 13561= 1125= 130002
=-24576= 7725= 73552= 132645
                       1125= 130002
                                                                     72606
                                                                     36449
=-28672=
              3772= 125673= 169130
                                          = 37600= 25245= 35404
                            Ø= 21461
                                                460000=
=-32768=
```

Single axis - 0 to 32,768 pulses and return to 0 again.

1	1	r							
1	^	1	_						
-	しまりつびに	րեր <u>յե</u> ր	. under (231777	556667	640088	10003C	603567	54376.
1	იქტილი	condac	646256	360000	SEGNOT	348886	2000077	oranau	14005
5	າຊກູກຳລັດ	800387	Cander	00000°	acara.,	640095	000000	phanea	೧೪೦೦೯
3	640006	000000	349331	202067	230707	047000	posech	acanaa	040207
Ē	սե ռաև և	5.06.000	: 4000 r	יפיסנד	רפפפרכ	242000	CCCOCC	ε ε ε ε ε	-FCJ
5	charge	լըորըո	040000	200000	120001	890045	teeern	פרניהכנ	[483 nn
ร	0,0000	งอักอีวา	ระกิสตา	accoin	սենորը	340 <u>0</u> 33	B65664	acanas	oαCio.
7	14 <u>7</u> 167	000000	.40050	անցերո	CCCCCT	24 1386	222207	იიიისი	(#[]Or-
£	Հ ԿԻՐԸԸ	0.0000	נייטנני!	100000	րընըըը	141000	ይር ይይሳቤ	07 07 6	14785
1	77777	177777	140361	0.00075	000000	J022#2	cecter	100005	יווויי
2	277777	177778	(40000)	100007	רבטרסס	247808	000001	030700	[77 77 4
2	~37777	177777	150000	accarr	ברמיוי	լերբըը	000071	170797	£3775°
4	r-7777	17777°	141661	-55	շրերը.	00000	100,00	ני יננ	C3775
5	-:1777	177757	1-1351	±66 30°	2,2605	_47000	605013	173733	~ * 7 7 7 3 °
6	~ 37777	177755	_ 1300tl	accear	0.00000	34303.	803013	000135	~37664
7	~*7777	177747	******	200070	105000	34°006	מבכפנים	15556	77611
2	77777	177740	องควอก	680000	220000	94788E	000004	190999	C 3 7 52 7
- 1	{ 77777	177747	147CCF	17736.	. %0000	547006	665567	1~6~.6	r3761°
- 4	~27777	177735		567337	i Tabr	847535	777335	מהפתם	u 3198.
- 3	77777	177757	140707	369671	-00005	649606	000005	101000	7777
- 4	~37777	17777	նկողըո	י ייטונ	ฉวอกสม	840000	000502	ממחקחם	~3774#
- 5	r 77777	177777	140000	pacuer	10000	34738C	000001	180000	^ 3776
- 5	22222	:77775	[47007	GCC*n	CCCCC	მოიიტტ	000001	פיניבנ	£27766
- 7	7 7 7 7 7 7	177777	140350	^0000.^	25577	347330	20200	10000	~ 7777
- £	ԵԿԵՐԵՐ	100000	רניני	~~~~	Իննսնն	240000	toches	פייכיננ	r7777r
- 1	ვაივცი	, 20205	լ ԿՌ յշր	050000	arabhu	24 ^ 00	อยอกวก	ברבים	r7777
- 2	C + OCCC	FC6.000	יליטני	, 00000	tetabt	34^606	ccocc	0.0000	2777
- 3	205040	000000	248557	ກວວວວດ	600000	ԵԿՈՇՕՆ	ooccer	coanau	r 7777
-4	იონნსი	200000	ይ 4 ሮር ሮ ሮ	מרטחט	recnoo	242600	מכסנטי	ממסימנ	- 7777
- 3	. r J o L c	107000	£40000	100001	20792	140000	LEOGUL	000000	77777
- b	იციიეი	canach	ნტიული	200001	GCCCCC	340000	00000	0,000	~7777
- 7	იტიბიი	CCCCG	ნამმან	JGCCCT	reared	247885	tracte	むからでして	(3777)
- 3	ፈቱ ገንኮቦ	מברטני	.400cm	accach	00 00 0	049500	300000	00000	~ 7777

Two axis x,y sequentially - 0 to 8 pulses and return to 0 again.

TABLE 5.2 (cont.)

C	1	1							
1	P	1		r					
=	000000	000000	94096C	000000	000000	040000	accer	00000	^060# <u></u> ^
1	£37777	177777	140000	ccooor	000000	04000L	GCGCCT	190000	r 37777
2	77777	177776	D#0027	000000	000000	040000	000001	00000	737774
3	G 37777	177773	140660	000000	000000	040000	GGGCCTI	199700	D 3776
t.	77777	177770	C4CCC0	200000	000000	040000	000002	000000	C 7775 '
ţ.	C37777	177763	140000	20,000	000000	047886	CC0C02	120000	C37727
Þ	ですすファフ	177755	LANCER	000000	220000	040000	200007	00000	C 37664
7	337777	177747	140000	300000	000000	040000	220003	100000	037611
٠	C37777	177740	C400Cr	000000	000000	640000	GEODO4	000000	C37527
1	037777	177737	140360	177777	100000	047100	600004	000000	C37527
2	£77777	177736	լենըը	177777	200000	040202	000004	000000	r37521
3	r7777	177737	140007	177775	1 00000	040313	000074	องอกออ	77527
4	r~7777	177720	64006C	17777E	LODOOC	047424	000004	200000	537525
5	C77777	177723	140067	177715	100000	040556	000004	000100	r 37521
6	0.77777	177715	0400GC	177775	000000	040706	000004	000000	C 1752
7	~37777	177787	1480CC (177774	100000	041968	000074	วถกลดด	F77527
•	77777	177700	ը«ՐԸըդ	177774	200000	041751	CCCCCa	000000	C7752-
- 1	C37777	177787	140000	177774	ממממינ	L41057	100074	000000	F77527
- 2	דקקליר	177715	0403CC	177775	000000	949794	000014	ghangh	r 77521
- 3	C27777	177727	146686	177775	100000	<u> 47545</u>	200004	anchee	r752°
- 4	44,444	1 777 30	C46000	177778	מחספסר	840426	FCCCU#		C7752°
- 5	737777	177733	140000	177776	100000	ეყივევ .	ԾԵՇԵՐ #	อยกอกอร	F 37527
- 6	677777	1 7 7735	640967 (177777	000000	C4^174	005664	enanaa	r 3752 ~
-7	737777	177737	140000	177777	1 10000	047771	000004	מברכנכ	C 3752
-6	£ 37777	177740	ԱԿԸննո	cooccc	accenc	027776	6000CG4	80E066	£37527
- 1	£37777	177747	148666	30000	000000	237770	F00000	100700	7761
- 2	G 3 7 7 7 7	177756	C48000	30000r	000000	077770	000093	~6~60	r ₹766~
- 3	037777	177763	1400CC	อดวอกก	000000	בלללנם	000017	הַסְיםים 1	~ * 7 7 7 7 ~
-4	037777	17777"	040000	000000	000000	03777n	000002	գրըոթը	227780
-5	(37777	177773	140030	000000	CODRCC	G37777	LCCGC1	1 ~ C ~ C G	237762
- 6	77777	177776	24356n	000001	GCCCCC	סדדדים	000011	ononat	~ ₹7765
- 7	737 77 7	177777	140000	סטפסטר	600000	C3777C	scour	176766	57777
~ 8	C4000C	000000	040000	COCOCO	CCCCOC	237776	000000	00000	77777

Two axis y,z sequentially - 0 to 8 pulses and return to 0 again.

1	'n	1							
1	2	1							
r	747777	000000	640001	60000n	adana	640390 F	300000	ananas	ეყვეი
1	\mathbb{S}_{σ} and \mathbb{G}_{L}	000000	_483£3	ენმე ეი	200004	045061	000000	ומרנים	C400C
2	040000	600000	640060	ინისი	200000	040000	ספפפפר	רפרסיים	040 <u>2</u> 0
3	240000	160000	6400ac	360000	רמימפט	040000 1	200000	อาดาอะ	74230-
4	ሮ4000ና	อดกออก	840380	3860 <u>0</u> 00	660001	340005	200000	proroa	746307
5	040001	565567	640000	າງຍວອດ	GEGNE	043303	papeer	วถวากา	14000-
6	Ա « ((Ը ՖԻ	CSSSSS	243000	205361	000000	340003	occcon	anore	14226-
7	040000	666697	64882n	000000	000000	£400CJ	200000	George	านอวิกา
8	C4606 C	030000	0823#3	100000	000000	3092#0	000000	อกตกษอ	14007-
1	737777	177777	140000	177777	100000	040003	000057	000700	1482F
2	C37777	177778	640660	177777	cocenc	מעייכ 20	מנפפפי	CCCCC	545555
3	£37777	177773	140680	177776	.0000	247216	הכסססר	ananse	r42311
4	037777	177770	J48338	177776	accons	047724	acecer	anonca	045-0
5	77777	177757	140000	177775	100000	C47650	350000	000000	านอัการ
-4	~~7777	177770	040000	177776	CCDDDD	044CS¢	000000	פסמפספ	£#50 [-
5	C37777	177773	140020	177776	1 0000C	04C03	000000	000000	046207
-F	r77777	177775	ՆԿՐԸԵՌ	177777	600000	C27774	000000	ნღლიდნ	ՐԱՇՕՐՐ
-7	דדדדים	177777	140000	177777	100000	C37771	CCCCCC	ופרכרט	14 C3 11
- 3	C + C + C + C + C	200000	648667	968335	966605	37777 _U	360000	ananas	040001
-1	543555	f00000	640586	000000	200200	ט777 ב	266662	20700	740077
-2	ՐԳԽՐԵԵ	00000	840000	900000	600000	037770	200000	prorco	ריסטפרי
- 3	040000	000000	D40CG0	000000	000000	237770	000000	000000	0.40201
-4	ՐԿՈՒԸՐ	เอกรอว	C47867	000000	000000	037773	000000	000000	2400C2
-5	043000	000300	640027	000000	000000	037772	000037	000000	n 4635
-6	ניייניני	cacaor	040000	200000	555550	C3777C	concor	0,6,00	
-7	646000	200200	E486E9	0.00000	600000	237770			7400 A.C
- 8	040000	000000	C40066	000000		1	202220	50000	04030
- 0	0.4020	uuccan	640660	กลกถูกเ	000000	037776	000000	007700	04006

Two axis x.z sequentially - 0 to 8 pulses and return to 0 again.

TABLE 5.2 (cont.)

1	1	1							
1	ą	1					•		
Ĉ	040006	000000	040000	900000	790000	04000ā	acerrr	apanaa	040001
1	040000	000000	5400CC	000000	000007	040000	peagar	000000	040201
2	040000	000000	040050	000000	000000	040000	000000	000000	04000°
3	040000	000000	040000	200000	200000	040000	000000	מפרפפם	0.40000
4	040000	ממסחסם	0400CA	000000	000000	040000	00000	000003	£ 4650°
5	147CCC	000000	CACCCC	930333	000000	040000	1.60000	010105	7403h
Ç Ç	ጋ4 በኃበጣ	დითული	040000	00000r	000000	040003	000000	כמייםנים	£4030°
7	040000	000000	263943	338333	100000	040000	מטפנים	change	-460 c
3	000000	000000	G4000n	000000	000000	040000	000000	phonos	00000
1	לללבבט	177777	140000	600000	000000	C4 C0 C C	CLOCGL	100000	r37777
2	じょうファフ	177778	D40C0C	000000	000000	040000	900661	. 000000	r37774
3	037777	177773	140000	3667366	200000	040000	173330	100,00	037765
4	77777	177770	E40000	rocarr	000000	54CC60	מבכרנ2	000000	(3775°
5	C37777	177763	140000	366900	200002	040000	000002	100100	C 3 7 72 7
ь	677777	177756	C400CC	200000	500003	040806	000007	20000	C37664
7	037777	177747	140900	000000	000000	040003	000063	10000	037611
- 7	537 777	177737	140000	177777	100000	042571	LCGCG4	ceenoo	C 3 7 5 2 ^
- 8	C37777	177740	040000	9336536	000000	03777C	000004	סמימנס	03752
- 1	£37777	177747	140055	000000	000005	337770	00000°3	190000	#3761 T
- Z	~ 77777	177756	0+5367	200000	606006	J*7775	5 00000	000000	P 7 7 86 1
- 3	<i>(277777</i>	177757	140000	Jeeser	000000	G3777C	200002	110100	53777
- 4	~37777	17777	240727	050000	000006	077770	000002	ocenac	737744
- 5	77777	177777	140300	0.00370	SCODOL	037770	000001	103700	737761
-6	C27777	177776	040000		COCCCC	037772	666661	ספרכרם	^377EF
- 7	77777	177777	1400007	955055	200003	53777J	adecen	100000	~3777~
- 8	540 33 1	000057	040077	apasan	600000	03777	acaero	כמיימתם	£3777 -
- 1	رو ٦٢ ٣٠٠	ุ่วยายอา	140000	100000	FC5000	C3777~	อยอกอก	307370	57777 ~
- 2	0#3377	6970an.	540 000	200021	300701	377772	300000	C00007	27777
	(#C2Ci	recesu	. 40557	Locate	cecees	63777_	000000	chonde	~3777~
- 4	040000	acogan	248634	000366	202202	237775	000557	200000	73777
-5	ייננטנ	000000	ნოუნნნ	50000	CCBDQC	03777L	200000	chence	r3777-
~ =	ሲቁተርበ <mark>ር</mark>	ccccon	նաններ	136256	CCOODO	03777L	25555	ocendo	r3777~
- 7	ር ሳ ካጋ ቤ።	200000	54 r \$	265327	0.00000	27777_	pasaan	202000	~7777
÷ =	1 F C መብር	100500	040556	78,786	ccccc	637776	000000	chenge	F7777-

Three axis x,y,z sequentially - 0 to 8 pulses and return to 0 again.

1	1	C							
I	1	P	:	I		a,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	00000	ดกดๆดด	040001
£	C4000°	300000	04CGC^	666990	000000	040000	000000	•	
1	04099r	500003	L48300	000000	000000	949999	000000	00000	040301
1	P37777	177777	140000	000000	COODOL	040000	CCCCCC	1,0,00	737777
-	037777	177777	140000	000000	000001	040000	086666	130702	27775
2	237777	177772	040861	000000	000001	047000	060001	פסמיספ	037777
-	C37777	177775	140000	cocooe	000003	840000 }	005001	ეინინნ	737765
3	C27777	177777	140660	ინშინი	000003	040000	000001	112180	~ 27757
_	237777	177777	140000	conner	000006	040000	000001	100700	£37745
4 4	037777	17777	3400Ch	200000	000006	040000	000002	phonop	037731
-	= -	17777	. #3000	000000	000012	040000	50,0002	granaa	C3771^
5	r37777		140000	06000r	000012	049003	000002	100000	77667
5	77777	177753	-	1		_		000000	C37566
-2	C37777	177755	040000	600000	C00017	040000	000003		
- 3	937777	17775*	140667	000000	000017	040000	000005	100000	737624
- 3	C27777	177703	140000	000000	000012	300700	000002	100000	C3765
- 4	537777	17777°	0400C^	000000	000012	340000	ספטנייצ	อดอกอก	73776
- 4	r:7777	17777	ՆԿՐԸԵՐ	700000	60000	040000	600002	ეიტიცნ	C37727
- 5	C37777	177773	140060	200200	000006	040006	000001	100000	C 3 7 7 3 4
- 5	037777	177773	140000	000000	000003	040000	000001	100760	037744
-6	C37777	177776	040000	000000	000003	847888	000001	ססיוםפט	C3775 7
-6	037777	177775	040000	oocoor	000001	040000	000001	2092	037756
-7	C37777	177777	140000	L00000	600001	040000	000000	100000	r3776^
-7	037777	177777	140000	000000	000000	040000	acecen	100003	r3776~
-	C4000C	n00000	040000	000000	000000	040000	000000	000000	C3776-
-8			640000	000000	000000	000000	200000	00700	C3776^
-8	C40000	00000	U+0000	000000	1100000	0-0000	1	222.00	

Two axis $\Delta x, \Delta y$ incrementally - 0 to 8 pulses and return to 0 again.

TABLE 5.2 (cont.)

G	1	1							
1	1	9					_		
5	Րաըրըր	acasan	035645	000000	0.000.00	64 0 663	กษาขอาเก	000000	34000°
1	~ 77777	177777	1-0000	000000	000000	040006	proces	ים ים ים פרו	237777
1	~77777	177777	გყოთლი	177777	1 00000	049001	อายาดา	100005	77777
2	C 27777	177775	140000	177777	1 60000	047001	ומרבנה	อานาอย	°77777
2	£37777	177774	240000	177777	coocac	040007	chanai	preroc	737777
3	77777	177771	149000	177777	000000	049007	Gusthi	inamat	737761
3	£~77 77	177767	ดนกตอก	177776	100000	04C~5E	อาจออา	1,50,00	~3776~
4	037777	177763	146366	177776	100006	048826	586817	მიმინმ	G3773*
4	037777	17776C	եկրցոր	177776	.80000	040062	CC00G5	00000	C3773°
5	037777	177753	148357	177778	000000	049962	000002	100000	r3766
5	037777	177747	0.4000.0	177775	160660	D#N137	000002	177700	7375FT
í	037777	177741	1 4000	177775	100000	04F137	דמרסרט	oranoo	۲۲ 757 ۲
ד	<u>ግ 3 7 7 7 7</u>	177734	247267	177775	000000	347241	86.3757	ტომოტა	C3757%
7	77777	177725	146667	177775	000000	643241	000007	178783	r 37455
7	C37777	177717	ՐԿԻՑԸՊ	177774	100000	04~374	GCC013	160000	C 37455
5	77777	177707	140500	177774	150600	G40374	ըքլու _ս	מפרטרס	C37304
- A	637777	177700	243755	177774	0.00000	047564	_0000		C17304
- 1	77777	177727	140-	177774	100000	C47373	303074	<u>ըսըրը</u> ս	r 3 7 3 7 4
- 1	- דר דר די	177717	248630	177774	100000	247373	מנסרכי	inshac ,	~3745°
- 3	77777	177725	140630	177775	500003	64~237	0677,7	125002	~7745~
- 2	C17777	177734	£477CT	177775	800000	G4~237	7 70000	gganga	r ₹757²
- 3	77777	177741	140000	177775	100006	040134	000003	פטיינים	C#757
د –	C 37777	177747	246227	177775	100000	G47134	000000	122000	ก 3 7 66 วิ
- 4	~~7777	177757	Inter	17777£	rc0666	<u> </u>	666707	176768	737667
- 4	~ ₹ <i>7777</i>	177757	649001	1 <i>1</i> 7777€	000000	047756	955577	acchec	~77775
- 5	237777	177763	140000	177778	100000	G40C21	F00005	001760	(3777
- 5	077777	177757	7333+0	17 77 76	100000	047021	555001	1-0-60	C3775?
- 6	מדדדים	177771	140050	177777	000000	04^061	000001	100000	r37751
-6	77 777	177774	040500	177777	180000	C40001	ביינים ש	000000	r3776=
-7	דרקדים	177775	140660	177777	100000	037772	550001	פפרכפ	2776
- 7	737777	177777	040CC	177777	1 00000	037 77 2	סטפריי	112106	73777
- 5	637777	177777	140000	000000	930002	677773	000000	10076	~3777
- 0	ეყლივი	aacach	040000	000000	000000	07776	occcn	დოდობა	r3777

Two axis $\Delta y, \Delta z$ incrementally - 0 to 8 pulses and return to 0 again.

ì	-	1							
1	1 C#3Cnn	ccetar	[4005-	500000	acenna	042300	accoon	วาเกอา	140961
1	243131	100000	249257	200521	200002	040000	PECUAU	enande	C483C
1	037777	177777	146565	177777	100000	#000C	000007	38788	_4CD0_
2	037777	177777	140000	177777	100000	០4៣៦០៩	363757	000001	1403C
2	~37777	177775	1 17300	177777	000006	640862	00000	200001	Ր4Ը35~
3	~~7~77	177776	(-reir	177777	tescor	84º06	70000	575 76 3	74887
3	~37777	177777	146000	177775	166060	040514	อกออกก	272773	არმამა
L.	C 77777	177773	140500	177776	100000	040024	636677	adrand	24886
4	C37777	177770	C#3000	177776	000000	040546	acccar	678786	[4GC[f
5	037777	177770	640000	177776	000000	040060	000000	070112	£4030
5	~~77777	177753	147856	177775	iccere	040104	CECCEC	67 671 2	146821
6	^~7777	177703	140555	177775	1,00900	04~134	300000	373717	040001
ŧ	77777	177756	646366	177775	FCCCOC	040172	כנברפר	CCCC17	1463f1
-2	C77777	177756	L48666	177775	CODGCC	040166	כנטנטי	606017	145Btr
- 3	£37777	177757	140000	177775	1,00900	047127	000001	270717	54955
- 3	737777	177767	140000	177775	100000	04^075	50000	C1C112	_#66 u.
- 4	~ 77777	17777	740501	177776	0.00000	047C5G	eecrar	2112000	0483 0
- 4	277777	17777	540500	177776	000002 1	040030	acaaar	673776	1400r
- <u>-</u> -	C77777	177773	1-6566	177776	100000	040613	sceene	300006	646365
- 5	737777	177773	140000	177776	100000	240001	000000	270783	~40~ 0 ~
-6	237777	177776	C40000	177777	_BD6C6	237772	200000	200063	ՐԿԸՕՐԴ
-6	~37777	177776	040000	177777	000000	337766	00000r	0 00061	იოცვი-
-7	£27777	177777	140000	177777	100000	037763	EC0000	13002	C4CC(^
- 7	~~77777	177777	140007	177777	100000	637761	aeansh	פטרטיט	040207
-â	140GCC	0.00000	5468BC	100000	CCCOOC	337760	ccooor	oronoo	740077
- 5	546600	000000	£4000C	ceooca	00000	C37760	בהמססטה	GCGUBE	1.4CO CL

Two axis $\Delta x.\Delta z$ incrementally - 0 to 8 pulses and return to 0 again. TABLE 5.2 (cont.)

1	1	1							
1	1	2	•						
ī	<u> Դ</u> Կ Ը Ը ՈՐԸ	F00000	649887	ougher	000000	ըգորը	Leegear	000705	n40331
i	C# 0330	900000	0.4000n	900000	300000	04850	acoser	0300GU	ՐԿԵՊԾՐ
1	237777	177777	140366	330000	500005	3460gJ	000000	100700	r 77777
1	237777	177777	ეონელი	177777	100000	040021	996637	100000	~ 37777
2	: 77777	177777	მოიული	177777	100001	34°031	מכפרמר	100001	077775
5	ריקקקי	177775	137775	177777	100001	340001	000001	010101	יזרדים
4	227777	177774	նգրըըո	177777	000001	047037	000071	500001	r ? 7 77°
3	037777	177774	64036F	177777	000003	040713	000001	000703	G 3 7 76 ⁻
3	£37777	177771	137772	177777	000003	849613	600001	150063	r3775^
3	937777	177757	0+CSCn	177776	100003	040032	000001	100003	r37757
Ļ	077777	177767	340357	177776	1 00006	048742	COCCCI	100006	r 3774
4	r=7777	177763	1277t #	17777€	10000€	647542	500002	30C13 6	r*771^
4	~37777	177760	040000	177775	600006	040075	000007	010104	יו777ים
5	237777	177757	54 C^ C^	177776	350912	047115	050012	87671Z	03767
- 3	C?7777	177747	1400CC	177775	100017	04 G 216	CCCCG2	150517	~*75 EF
- 3	77777	177747	546757	177775	100012	B47154	888645	100012	737615
- 4	77777	177757	1377-4	177776	L00C15	C4C136	000007	100012	r3761¢
- 4	77777	:77765	լգրոցո	177776	00012	040186	000007	866615	r3765^
- 4	~ 77777	177750	Ե4^Ω^ ~~	177776	C 500C =	847666	000012	じつつべひる	-37 <i>1</i> -2
- 5	(77777	177753	4 د 1377	177776	100000	040031	000002	₽~C ~3°	7777
- 5	~ * 7777	177767	04F05f	177775	100006	040731	000001	190036	C21121
- 5	77777	:77767	047888	177776	100003	G40017	200001	10003	רדקרים
- 5	737777	177771	137777	177777	000003	037777	000001	100003	~~7737
- ĉ	27777	•77774	647377	177777	000003	037777	000001	בפחפים	r 3775'
- €	77777	1777 7 4	647636	177777	L00001	037773	0000031	occrei	r*7756
- 7	27777	17777=	137776	177777	100001	037764	000001	000001	c 7775~
- 7	יידייי	177777	040000	177777	100001	037764	DEDOCT	166461	r3778 -
- 7	037777	177777	848667	177777	100000	337762	000000	192000	7778
- 8	~ 37777	177777	140550	חרטטטט	000000	03776_	000000	100000	~ * 7 75~
- <u>z</u>	ניינננ	, 00000	อันกรรก	FESSSE	ccccoc	237767	CCCCor	ըրըրըը	737767
- 3	044550	066330	340050	000000	000000	077750	000000	<u>פריפרס</u>	~ 7776~

Three axis $\Delta x, \Delta y, \Delta z$ incrementally - 0 to 8 pulses and return to 0 again.

1	1	ŗ							
16	128	1							
D	040000	000000	040000	000000	000000	040000	000000	000000	610047
15	640000	000000	040000	000000	000000	040000	000000	000000	04000^
12	^4 COOO	000000	040000	000000	000000	040603	ooocor	00000	04000^
43	040000	200007	040060	000000	000000	040000	000000	000000	700047
£4	րալը <u>ը</u> ը ըր	000000	040000	000000	000000	840608	000000	000000	C40000
3L	00000	000000	5400CC	acosen	000006	040000	oeseec	000000	040007
36	ը ս ընցոր	200200	ევშეఖე	506666	5000000	040000	000000	309930	C4602cc
112	840000	000000	0408¢C	000000	000000	£4000J	200000	00000	04000~
178	040000	000000	040000	000000	000000	040000	סכפכסת	000000	C#08CC
18	C77777	177600	646000	LDDDGD	000000	040000	666617	იღითიი	035247
32	037777	177000	030040	986336	000000	040000	000021	693999	n12501
4 ∂	~~7777	175600	040013	000000	000000	040606	000027	177777	127754
#4	77777	174CCE	C40047	000000	000000	04 000C	000037	177776	165234
- 32	r 77777	167000	04N3 4	ออดรวก	000000	047000	000057	177773	1 #0 234
- 4-	(77 777	17160~	04C1Z~	222303	600000	040000	360647	177775	122574
- 54	27777	174007	040325	ინცემი	000000	040000	000037	177776	165334
- ÷ C	77777	175600	C27767	000000	000000	040006	000027	177777	170074
- 95	C37777	177200	C37753	000000	000000	០4៣០០៤	000023	00000	-1263
-112	~?7777	177605	[377±7	PDEDEE	000000	040000	ርር ይኖ 1 ሰ	פטריטט	£3535°
-125		200000	C37757	000000	COOPOO	040000	սընրըր	ออกอกอด	~4LG7
-16	648666	COGGGC	037753	000000	000000	040000	BSCCOr	898486	04637
- 32	C40000	000000	037753	0000000	600000	040000	200000	200000	T4CC7 -
- 43	040000	900000	C37753	900000	000000	040000	00000	000000	240077
- £ 4	აოციილ	000000	037753	ՐըըըԸ	000000	000040	000000	90 0~0 0	C40075
- 30	040200	002000	C37753	000000	000000	040000	acacar	מפתמתם	C4037
- 95	040000	000000	G3 7 753	600000	000000	040000	000037	000100	04037
-112	797797	៩៤០០០០	637753	CCCBGG	000000	042600	ccccat	200700	740077
-125	04000°	00000	C37753	566630	000000	040000	000000	000000	54037

Two axis, x,y sequentially - 0 to 128 pulses and return to 0 again.

TABLE 5.2 (cont.)

С	,	•							
18	127	1							
Č	しがしこりと	กอวออด์	240085	000000	000000	04°C06	נפטככר	פרקיננ	~40D~~
l ə	מיקקים.	177600	C400E0	000000	000000	545006	060617	อกบาตอ	C 3524 -
3.	ידללנח דדלליח	177000	240050	000000	999999	040000	3000 Su	0,0,000	€125€
4 c 6 4	C 77777	1756CO 1740OO	640Cl 3 840947	000000 000000	000000	040000	000027	177777	1277=4
30	(7777 7	171500	640143	750300	000000 000000	040000 040000	888237 888647	177776 177775	1 55234 1 72 51 4
3 É	£77777	167000	0403_7	COSOSC	200000	040000	500057	177773	177774
112	277777	163500	340635	0.00000	000000	04000C	000067	177771	۲15254
12= 16	~27777 ^27777	16^000 157600	041233	200000	000000	040000	000077	177765	112534
72	027777	15760C	041333 C4163₹	17777C 17776r	000004 000010	042523 055240	060977 060077	177765 177765	112534 112534
48	c37777	155500	C42341	177750	000014	147750	000077	177765	112534
54	r37777	154000	C43271	177740	000021	112500	000077	177765	112534
9C 96	277777 777777	1516CC 1470OC	C44461	177730	000026	155220	CCOC77	177765	1125 74
112	037777	14350C	C46132 C50114	177720 177710	000034 000043	13774G 062460	0C0C77 0G0O77	177765 177765	112534 112534
123	037777	140300	(52435	177700	000052	165200	000017	177765	112534
-1 b	77777	143260	85°875	177710	C00043	06244	000077	177765	112534
-22 -43	לדליים לדללונ	.47000	G45.7F	177720	000034	137700	060077	177765	112534
-54	237777	15160N 154000	644411 043267	177736 177740	000026 000021	155140	200077	177765	112534
- 30	C37777	155607	042245	177750	000014	112400 147640	77,0000 77,0000	177765 177765	112534 112534
-96	037777	157460	C4152F	177760	000010	065100	000077	177765	112534
-112 -123	537777	157500	641315	177770	000004	042340	000077	177765	112534
-15	237777 237777	1670DC 16368C	841112 640455	000000	000000	037600 037600	660677 660667	177765	112534
-32	237777	167000	G4C163	000000	000000	037600	000057	177771 177773	C15274 140634
-48	C37777	171600	£40002	000000	00000	G37600	000047	177775	122574
-64	C 37777	174000	637764	opagan	000000	037600	000037	177776	165334
-9C -=6	רדיוי (דיויי	1756GC 17755C	037646 037512	£0036C 20006C	000000	037600	000027	177777	170074
-112	27777	177600	037637	000000	000000	63760C 03760G	000020	00000	F1267 035357
-12.	~# 3667	000000	637637	00000	00000	037600	713838 793838	000000	
-126			C37637	C0 C0 00	000000	037600	000000	000000	C4007-
-12.	Two ax		C37637	C0 C0 00	000000	037600		000000	C4007-
1	Two ax		C37637	C0 C0 00	000000	037600	000000	000000	C4007-
1 16	Two ax 0 128	is, y,z	c37637 sequent	cococo tially - 4	ccosos 0 to 128	037600 pulses	occcer and return	to O a	r4007- again.
1 16 0	Two ax 0 128 040000	is, y,z	c37637 sequent	cocceo tially = 4	ccoooc 0 to 128	037600 pulses	occcer and return	to 0 a	04007- again.
1 16 0 16	Two ax 0 128 040000 040000	is, y,z 1 1 000007 00000C	C37637 Sequent	cocceo tially = (ccoccc 0 to 128	037600 pulses 040000 040000	occcer and return occcer	to 0 a	r4007- again.
1 16 0	Two ax 0 128 040000	is, y,z	c37637 sequent	cocceo tially = 4	ccoooc 0 to 128	037600 pulses	occcer and return	to 0 a	04007- again. 04090-
1 16 0 16 32 48 24	Two ax 128 040000 040000 040000 040000	is, y,z 1 000000 000000 000000 000000 000000	C3763? Sequent C40000 C40000 C40000 C40000	cocco tially - + coccoc coccc coccc coccc	0 to 128 0 coocce 0 coccc 0 coccc 0 coccc	037600 pulses 040000 040000 040000 040000	ececer and return eecece eecece ececec ececece ececece	to 0 a	04007- igain. 04090- 04090- 04090- 04090- 04090-
1 16 0 16 32 48 54	Two ax 128 040000 040000 040000 040000 040000	is, y,z 1 1 000000 000000 000000 000000 000000	C3763? Sequent 640000 040000 040000 040000	cocce tially - (cocce cocce cocce cocce cocce cocce cocce	0 to 128 0 occord 0 coccoc 0 coccoc 0 coccoc 0 coccoc 0 coccoc 0 coccoc	037600 pulses 040000 040000 040000 040000 040000	ecocor and return ecocor ecococ ecococ ecococ ecococ ecococ ecococ ecococ ecococ	to 0 a	04007- again. 04690' 04600- 04000- 04600- 04600-
1 16 0 16 32 48 24 30	Two ax 128 040000 040000 040000 040000 040000 040000	is, y,z 1 000000 000000 000000 000000 000000	C3763? Sequent C4000 C40000	cocce tially - (000050 000050 000005 000006 000006 000000 000000	0 to 128 0 000000 000000 0000000 0000000000000	037600 pulses 040000 040000 040000 040000 040000 040000	and return accecc	to 0 a	04007- again. 04090 -40004000400040004000-
1 16 0 16 32 48 54	Two ax 128 040000 040000 040000 040000 040000	1 1 1 000000 000000 000000 000000 000000	C3763? Sequent C40000 C40000 C40000 C40000 C40000 C40000 C40000 C40000	cocce tially - (0 to 128 0 occord 0 coccoc 0 coccoc 0 coccoc 0 coccoc 0 coccoc 0 coccoc	037600 pulses 040000 040000 040000 040000 040000	ecocor and return ecocor ecococ ecococ ecococ ecococ ecococ ecococ ecococ ecococ	to 0 a	04007- again. 04690' 04600- 04000- 04600- 04600-
1 16 0 16 32 48 54 30 96	Two ax 128 040000 040000 040000 040000 040000 040000	is, y,z 1 000000 000000 000000 000000 000000	C3763? Sequent C4000 C40000	cocce tially - (000050 000050 000005 000006 000006 000000 000000	0 to 128 0 000000 0000000000000000000000000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 042520	and return and return accecc	to 0 a	04007- igain. 04000- 04000- 04000- 04000- 04000- 04000-
1 16 0 16 32 48 54 30 96 112 128 16 32	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 040000 040000	1s. y.z 1 000000 0000000 0000000 0000000 000000	C3763? Sequent C40000 C40000 C40000 C40000 C40000 C40000 C40000 C40000 C40000	cocce tially - 4 cocce cocce cocce cocce cccce cccco cccco cccco cccco cccco cccco cccco cccco cccco cccco cccco	0 to 128 0 000000 0000000 0000000 0000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 042520 055243	occer and return pagger	to 0 a	04007- again. 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600-
1 16 0 16 32 48 54 30 96 112 126 16 32 43	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 040000 040000	1s. y.z 1 000000 000000 000000 000000 000000 0000	C3763? Sequent C40000	000000 tially = 6 000000 000000 000000 000000 000000 0000	0 to 128 0 000000 0000000000000000000000000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 047754	and return accer	to 0 a	04007- 1gain. 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 04000-
1 16 0 16 32 48 54 30 96 112 126 126 143 54	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 037777 037777	1s. y.z 1 000000 0000000 000000 000000 000000 0000	C3763? Sequent C4000 C40000	000000 tially = 0 000000 000000 000000 000000 000000 0000	0 to 128 0 to 128 0 00000 00000 00000 00000 00000 00000 0000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 047520 255243 147754 117700	and return and return accept	to 0 a promote the control of the c	04007- again. 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600- 04600-
1 16 0 16 32 48 54 30 96 112 126 16 32 43	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 040000 040000	1s. y.z 1 000000 000000 000000 000000 000000 0000	C3763? Sequent C40000	000000 tially = 6 000000 000000 000000 000000 000000 0000	0 to 128 0 000000 0000000000000000000000000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 047754	and return accer	to 0 a	04007- igain. 04000- 0400-
1 16 0 16 32 48 44 326 1126 126 323 44	Two ax 0 128 040000 040000 040000 040000 040000 040000 040000 040000 047777 037777 037777	1s, y,z 1 000007 000007 000007 000007 000007 000007 177607 177607 177607 177607 177607 177607	C3763? Sequent C40000 C4000	000000 tially = 0 000000 000000 000000 000000 000000 0000	0 to 128 0 000000 0 to 128 0000000 000000 000000 000000 000000 0000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 047520 055240 147764 117704 117704 117644	and return and	to 0 a osoner Georee enance	04007- igain. 04000- 0400- 04
1 16 0 16 32 48 40 40 40 40 40 40 40 40 40 40 40 40 40	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 040000 07777 037777 037777 037777	18. y.z 1 0000000 0000000 0000000 0000000 000000	C3763? Sequent 6400000 6400000 640000 6400000 6400000 6400000 6400000 6400000 640000	cocce tially - (0 to 128 0 000000 0 000000 0000000 0000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 055240 147754 117700 155140 147644 035100	and return and	to 0 a conec cone	(4007- igain. recon-
1 16 0 16 32 48 30 46 1126 126 323 44 746 746 747 747 747	Two ax 128 0400000 0400000 04000000	18. y.z 1 000000 000000 000000 000000 000000 177600 177600 171430 171430 175540 177600	C3763? Sequent C4CCC C4CCCC C37757 CC77=3	000000 tially = 0 000000 000000 000000 000000 000000 0000	0 to 128 0 to 128 0 00000 000000 000000 000000 000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 047524 147754 117700 155144 117400 147600 147600 147600 147600 147600	and return and return accept	to O a source scorec source	040077
1 16 16 16 32 48 44 45 41 12 46 47 47 47 47 47 47 47 47 47 47 47 47 47	Two ax 128 040000 040000 040000 040000 040000 040000 040000 037777 037777 037777 037777 037777 040000	18, y,z 1 1000000 0000000 0000000 000000 177600 177600 177600 177600 177600 177600 177600 177600 177600	C3763? Sequent C4CCC C4CCC C4CCCC C37767 C37757 C277=3 T7753	cocces tially (cocces coc	0 to 128 0 000000 0 000000 0000000 0000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 055240 147754 117700 155140 147644 035100	and return and	to 0 a conec cone	04007- igain. 04000- 0400- 04000- 04000- 0400- 04000- 04000- 04000- 04000- 04000- 04000- 04000- 040
1 16 16 16 16 18 18 18 11 12 16 16 17 18 18 18 18 18 18 18 18 18 18 18 18 18	Two ax 128 0400000 0400000 04000000	18. y.z 1 1 000000 000000 000000 000000 000000	C3763? Sequent 6400000 6400000 640000 640000 640000 640000 640000 640000 640000 640	cocce tially - (0 to 128 0 to 128 0 000000 0 000000 0 000000 0 000000 0 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 040000 047520 147764 117104 117400 147646 04720 04720 047760 047760 047760 047760 047760 047760	and return and	to O a construction of the	04007- 1gain. 1 40000-
1 16 0 16 32 48 40 40 40 40 40 40 40 40 40 40 40 40 40	Two ax 128 040000 040000 040000 040000 040000 040000 040000 037777 037777 037777 037777 040000 040000	18. y.z 1 1 000000 000000 000000 000000 000000	C3763? Sequent 6400000 640000 6400	cocces tially (cocces	0 to 128 0 to 128 0 00000 000000 000000 000000 000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 157140 117700 157140 117700 157160 17760 17760 17760	and return and	to 0 a construction of the	04007- igain. 040000- 04000- 0400- 04000- 04000- 04000- 04000- 04000- 04000- 0400- 04000- 04000- 0
1 16 16 16 18 18 18 18 18 18 18 18 18 18 18 18 18	Two ax 128 040000 040000 040000 040000 040000 040000 040000 037777 037777 037777 037777 040000 040000 040000	18. y.z 1 000000 0000000 0000000 000000 000000	C3763? Sequent C4CCC C4CCC C4CCCC C37757 C37757 C37753 C37753 C37753	000000 tially - (000000 000000 000000 000000 000000 0000	0 to 128 0 to 128 0 00000 000000 000000 000000 000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 047600 047775 117700 147640 147640 147640 147600 147600 147600 147600 147600	and return and and return and	to 0 a a a a a a a a a a a a a a a a a a	C4007- Igain.
1 16 16 18 18 18 18 18 18 18 18 18 18 18 18 18	Two ax 128 040000 040000 040000 040000 040000 040000 040000 040000 040000 0407777 037777 037777 037777 037777 047777 040000 040000 040000	18, y,z 1 1000007 000007 000007 000007 000007 177607	C3763? Sequent C4CCC C4CCC C4CCCC C37767 C37767 C37763 C37763 C37763 C37763	cocces tially (000000 000000 000000 000000 000000 0000	0 to 128 0 to 128 0 00000 000000 000000 000000 000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047520 157140 117700 157140 117700 157160 17760 17760 17760	and return and	to 0 a construction of the	04007- igain. igain. 040000- 04000- 0400- 04000- 0400- 04000- 04000- 04000- 0400- 04000- 04000- 04000- 0400
1 16 16 16 18 18 18 18 18 18 18 18 18 18 18 18 18	Two ax 128 040000 040000 040000 040000 040000 040000 040000 037777 037777 037777 037777 040000 040000 040000	18. y.z 1 000000 0000000 0000000 000000 000000	C3763? Sequent C4CCC C4CCC C4CCCC C37757 C37757 C37753 C37753 C37753	cocce tially (cocce cocc cocce cocce cocc coc	0 to 128 0 to 128 0 000000 0000000 0000000 0000000 000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 040000 040000 047777 117760 117640 117640 117640 117640 117640 117640 117600 1177600 1177600 1177600 1177600 1177600 1177600	and return and	to 0 a second consideration of the consideration of	04007- 1gain. 1gain. 140000- 14000-
1 16 0 16 2 4 4 4 0 6 2 5 4 4 4 0 6 2 5 4 4 4 0 6 2 5 4 4 4 0 6 7 2 5 6 2 5 4 4 0 6 7 5 6 2 5 6 7 5 6 2 6 7 5 7 5	Two ax 128 040000 640000 640000 640000 640000 640000 640000 637777 637777 637777 637777 677777 64000 640000 640000 640000	18. y.z 1 1000007 0000000 0000000 0000000 177607 177007 1774007 177407	C3763? Sequent C4CCCC C37767 C37763 C37763 C37753 C37753 C37753 C37753	000000 tially = 0 000000 000000 000000 000000 000000 177776 177750 177750 177750 177750 177750 177750 177776 000000 000000	0 to 128 0 to 128 0 000000 000000000000000000000000000	037600 pulses 040000 040000 040000 040000 040000 040000 040000 040000 047000 047000 147760 155140 155140 147600 147600 147600 147600 147600 147600 147600	and return and and return and	to 0 a source to	040077- 1gain. 1gain. 1400000000000000000000000000000000000

Two axis, x,z sequentially - 0 to 128 pulses and return to 0 again.

1	1	1							
1 2	12-	1							
	~1 ~~ C~	լնորնո	Synung	100000	ւցցցու	C4700L	בנברפר	ברברפנ	747377
10	240385	000000	Lancer	300000	E 8000 B	ეფიიეს	accoon	200001	14885
32	ეფიემი	000000	ಬಳಗಾರವರ	300000	200000	240005	066697	הכתפים	198361
4 6	040000	600000	D#000n	000000	000000	040000	000000	ეომონე	ግዛር ጋጥ፣
54	ერისმე	000000	ეფიუნი	ეფტუიი	מממממים	347595	000000	_כייניני	_48_0°
ي (Q4 3 16 1	-5500	U47387	000011	170002	14768U	pageen	anemat	14850
26	747777	CGCCCC	0400EF	000000	<i></i> բեցոր,	344000	aggear	202721	14031
.12	1435G1	Concor	640000	000060	CCOCGC	U47000	LEGETT	<u> Շոկր</u> ըը	~468~~
123	343830	000000	040900	000000	30000	ՇԿՐԸՕՆ	886875	610 1 62	P4G3f7
1 6	r7777	177567	LACCOR	200002	200000	340000	000011	בכרפמס	~ ~ 5 24 ~
32	77777°	177000	247720	000000	000000	949093	000020	ananas	12511
و با	577777	175.50	640017	racaet	ւներնե	847886	660027	17777 7	177756
ξu	רקקיים	174LCF	L40147	100337	(00000	540505	526337	177776	155234
36	77777	171507	640143	2000023	000000	641386	3 20047	177775	172514
95	737777	167000	C4C35C	coccer	COCCCC	540668	G66657	177773	137774
112	r?7777	163600	646785	200000	COGCOG	847888	CC C067	177771	F15254
-112	~77777	157300	L41216	177776	666604	_4?34 <u>5</u>	000r <i>17</i>	177765	112534
-126	~ ? 7 7 7 7	160000	041112	cossor	CCCCCC	77670	060077	177765	112534
-16	C37 77 7	163655	240455	000000	000000	77F CO	060067	177771	C15274
- 32	C37777	167000	040163	000000	000000	306770	669657	177773	148034
-43	C 37777	171507	040052	000000	000000	3775 3 6	300047	177775	122574
-54	r37777	174000	037704	000000	00000	206776	000037	17777	155376
- 8 C	227777	175600	C37£48	200300	000000	237600	GCGC27	177777	130074
-96	G37777	177000	G57637	000000	000000	037500	00000	000700	~1263^
-112	~37777	177530	G37632	000000	000000	037600	000010	000700	035351
-126	ՐԱՐՐԵՐ	000000	C37632	000000	000000	637600	COBBOC	000000	~4607~
-15	C#0C0~	- 007337	C37632	000000	000000	937600	מהמממם	000000	C40071
- 32	r*ccc	CCCCCC	C27632	COBOGE	000000	037600	200000	00000	C4C07
-48	700047	900000	037632	000000	0.00000	037500	B£ 0861	000000	040077
+54	240000	ουαους	037632	0000000	000000	037600	ooooor	ססיפפם	040077
- 8 C	040000	000000	037632	000000	000000	037600	200000	פפפפום	C4687r
- 96	040007	000000	017632	000000	000000	037600	000000	מסיסכם	C 40077
-112	_# 56 C	pochor	C37632	55,000	CCOCDC	203750	555006	ნინანი	74C077
-128	P40300	366989	037632	200000	000000	037600	000000	פסרסתם	046071

Three axis, x,y,z sequentially - 0 to 128 pulses and return to 0 again.

1	1	û							
16	1	129							
_	740000	500000	64086 0	298903	000000	Ე ᲬᲝᲘᲔᲘ	00000	000000	L#00 L L
15	037777	177617	140000	000000	000170	04000.	000007	1º6º00	r 33261
16	C37777	177600	64836C	200200	000170	040000	000010	ספרספס	n ፣ 2 78°
32	D37777	177037	140002	000000	000760	03777°	000617	077777	1 70 14 5
32	C37777	177000	040363	000000	000760	037776	098017	177777	16830=
4 =	737777	175657	140727	300300	002150	037751	000027	377777	C26465
43	237777	175600	040031	000300	002150	G37751	008327	177777	r?214°
54	C*7777	174077	140115	200000	GD374C	C37F6_	CECC37	277775	12645
54	637777	174000	040127	000000	003740	037650	000037	177775	116565
80	r:7777	171717	140301	, 00000	CD613C	037470	000047	077773	C27724
50	C37777	171600	649313	000000	006130	03747	000047	177773	C13446
۵ و	C37777	167137	147627	200000	G1072C	G77135	CECCS7	677767	272645
3₽	C37777	167000	[4ቦ፥ዳ]	reader	C1672C	G77136	066657	177767	רקוטרי
- 1 b	~~7777	163500	641	ssesen	614110	235375	000057	177762	007377
- 32	r-7777	167000	[4[536	200330	011060	G3713C	CLOC57	177767	277121
- 32	こマフフフフ	167000	049536	000000	010770	077152	000057	177767	051105
- 4 8	C27777	171500	C4C274	100000	006750	037475	000047	177772	1772
-43	r-7777	171500	647274	cacaar	006130	037510	055^47	177773	-13 ec.
- 6.4	77777	174000	C4CC77	20,000	604040	G 77674	DECC37	177775	17677
- £ 4	~~77777	174600	(40077	cococe	GC374C	77761	SCCC37	177775	11675
- AC	£37777	175600	349533	000000	362236	337775	000027	177777	51635
- 36	037777	175600	646363	000000	262156	337772	000027	177777	U 2 5 4 LL t
- ap	e37777	177000	C37755	000000	001026	040017	GCG617	177777	164504
- 3 E	ハマフフフフ	177300	637755	600000	600760	04^020	066617	177777	1ĸ65₽ĸ
-112	C37777	177603	0.7750	300000	000216	04923	GCCClr	000000	72554
-112	~ 77777	177600	037757	000000	000170	049223	000017	00000	r 3315º
-12:	140560	000000	637752	200000	000000	040023	000000	00000	C4651r
-128	049000	000000	C77757	000000	000000	849723	00000	ממיימסמ	C40214

Two axis $\Delta x, \Delta y$ incrementally - 0 to 128 pulses and return to 0 again. TABLE 5.2 (cont.)

٤	1	1							
15	1	128							
С	047060	207007	լարեր	recost	200000	841096	accean	CABAGO	1400ff
1	577777	177417	1+0000	177775	100000	244473		agenas	
1 c	537777	177460	240057	17777	200000		669617		r 32 71 -
32	037777	176537	142804	17776	100000	045450	0CC01F	იოდონი	L3521.
3.5	077777	175000	048335	17775°	000000	107561	060017	177777	166227
45	627777	177457	1470.5	17775		113520	000017	177777	156227
4	~~7777	17 74 31	247237	1777*n	1 00001	051250	000027	177777	072157
64	7777	170677	147 3=	177740	000001	06717.	GCCF 27	177777	Π?215?
۴L	77777	17000r	L40347	177740	1 00502	15134	600037	177775	11657
3.5	037777	163517	1406:1	17773r	000000	17124.	000037	177775	11650
έč	F77777	1634CP	[4[62]	177730	1 00005	650030	005547	177775	013437
3 7	27777	156137	141471		207022	100710	000047	177773	013437
ຣ໌	7777	156737	C41517	17777	100011	005120	000157	177767	056757
112	27777	147537	147014	177720	LCCC11	Γ5Γ76⊾ 2007€	CC 2057	177767	750767
112	277777	147400	14 1. C4 C+324C	177710	100016	047515	000F57	177767	206717
122	037777	140177	145122	177716	100016	121435	20067	177762	rc671 ⁻
120	737777	140000		177700	100025	032705	000077	177753	C 7 5 24 ^
-15	דדדדים		C45174	177710	CG DC 25	132500	CEGC77	177753	5242
	S77777	147217	143742	17771	000016	121413	036676	877761	125551
- l o		147437	643365	177710	000015	121412	000057	177762	57573
- †2 - 32	777777 237777	155637	14145	17772	00011	C50720	$acace_a$	677767	C74581
		156000	E41433	177720	000011	050722	000057	177767	051827
۾ <u>ب</u> ا –	C27777	163257	146537	177730	200005	100530	66065C	C77772	182371
-45	77777	153400	247524	17773n	000005	100530	0 G0C47	177773	r13517
-54	027717	157577	140135	177740	000002	17114C	020041	377775	276551
-54	C37777	170000	54013r	177740	000002	171140	5GCC 37	177775	1166 C^
-85	037777	173317	137742	17775C	966661	G67C50	000039	G77777	C11211
- ĉ L	637777	173400	C 37740	177750	600001	0E2556	000027	177777	C2227^
4°E	C27777	175737	137664	177760	200006	113366	000020	C77777	152321
- 95	077777	175900	537657	177750	000000	113350	000017	177777	156367
-112	77777	177257	137654	17777	, 20500	04527(000017	10000	r72014
-112	77777	177487	57554	177770	200000	045273	000010	000000	733334
-12c	C37777	177777	157654	100000	בכבפנט	C3768C	Jeacan	100006	C461 C5
-128	940990	262896	~ 77554	000000	000000	0,7500	000000	סמימים	040104

Two axis $\Delta y \cdot \Delta z$ incrementally - 0 to 128 pulses and return to 0 again.

1	,	1							
1:	1	12-							
u	949991	565557	40060	000000	000000	ყორევა	pobean	000000	n 400m
1 =	:37777	.77.17	149005	17777	100003	244462	062537	093176	P4608
16	C37777	177500	U48331	177770	000000	345740	000000	000170	040361
32	C77777	177737	140002	17776	100000	107540	cconor	600760	53777F
3.2	77777	177030	84ngt3	177760	000003	111504	988777	010760	03777°
45	77777	17557	1405.12	177750	130001	J5127.	CSSEST	C12150	27751
ħ -	C 27777	175400	147031	1777:~	CCOPO1	C=554F	DECOUR	002150	C37751
54	237777	174277	140115	177740	106002	151300	acccor	Br 3740	~7765~
£ 4	F37777	174566	5401/2	177740	000002	191200	000000	-003746	C37665
3.5	877777	171717	1+0321	177730	180005	047760	000000	006130	C3747"
8 □	77777	171660	C40:13	177736	600005	884246	160670	006130	r3747~
36	77777	167137	140527	177723	100011	805240	000001	510726	C 3713"
- 1 c	225222	163560	C41417	177715	£65018	577736	000000	214118	~ *637*
-32	77777	167339	247535	177720	000011	პ ნეგშე	a665 .n	011760	~3713~
- 3 -	5-7777	167000	840035	177725	L00011	GPFEBS	cccccr	316726	737152
- 4 c	£37777	171560	648273	17773ቦ	00000	100006	SCOFOR	DP675C	r37475
- 48	C17777	17150	640313	177730	000005	054198	accean	076137	r 3751 °
- 74	רודד"ו	174000	240075	177747	000002	171000	SECUSO	284740	577674
- 74	~~7777~	174030	J47 7°	177740	CCOnra	16170	20,0225	C^274	ורךקיר
- 30	C ~ 7 7 7 7	175336	_4857	177730	000001	361735	CUCCTT	C^273	77777
- 3 🛴	2-7777	175900	E 4 L 25 3	17775	200601	255300	366674	002156	r 77777
- 75	237777	17756^	2,7755	177750	000000	113200	0.5000	641520	340617
- eé	~~7777	177560	[777-5	177760	CCDCQC	111200	הנפנינ	ՐՊը76Ը	C4GC2~
-112	1222	177521	C377 57	177776	300000	S45105	St 0777	וויםים	0488223
-112	F-~-7-	177 _ [2377 7	177775	.cores	144 Cr	^	200172	C4[27]
-123	30220-	იმციენ	こ 7737	190000	ეიიიის	u37402	CLECCT	onanan	040027
-12c	64666	000000	L 27722	200000	000000	077400	LECOMM	000000	040027

Two axis $\Delta x.\Delta z$ incrementally - 0 to 128 pulses and return to 0 again.

TABLE 5.2 (cont.)

ì	1	1							
15	1	123							
r	4400cc	ანღნნი	040_00	יונ במסט	Labora	ნყიიეკ	000000	phonoc	04000
15	037777	177437	2,0750	177770	1 301 78	24771.	000007	100170	£ 127 ነ
1 2	N37777	177417	137477	177775	100170	347714	000010	000177	£ 35 -
1 c	77777	177465	£40001	177773	GCG170	347776	060011	000170	0.30,35
- 2	077777	176777	C40017	177760	100760	134012	000017	100757	145554
٠.	£37777	17F237	177027	177715	1007FC	134012	מנמהאה	0°C75 7	141717
32	~37777	17,000	[t] [t	1777 +	003760	177752	085020	000757	141717
4 ,	77777	177537	047164	177750	162151	155763	368637	102146	175777
u -	~*7777	173457	133567	177750	102151	156763	CCCC 30	GC2146	114227
4 5	C37777	177467	E40112	177750	002151	167733	010030	002146	114277
٠ ٢	וודווים	170177	_4734F	177745	103744	017547	01 0037	103734	rs7147
3 **	~?7777	176277	1,0455	177740	153744	17547	000°4°	5°3734	C47445
54	227777	170200	Ე ୱ^3355	177740	003744	,37547	00SC40	573734	- 47445
•	637777	183537	2-1114	177750	106137	156375	665647	106126	134154
°Ç.	~37777	163517	124643	177730	105137	155375	000050	006120	173537
- 4 -	~~777~	157407	541744	177730	CC5140	GC7133	060057	576125	1 7 3 41 7
- 5 4	-27-77	187577	170170	177745	CD4C44	047756	CCCC4C	1 ~ 4 ~ 3 4	r1717°
- 54	~ ~ 7 7 7 ~	.7~627	247/50	177746	064044	247350	000047	D04034	~~727
tı	-7777	170000	じゅつきゃか	177747	LD3744	522250	G55647	C ~ 3 7 3 4	547355
- ac	~ 77777	173317	127322	17775C	GC2231	174551	250037	172226	~ 75 33 *
٦٤ -	~~7777	173400	J37774	177750	, 002231	174351	acensh	272726	10741
- ÷ [r = 7777	173400	L = 77.74	17775C	CG2151	167464	502037	D02146	114511
- FE	77777	175737	135533	177758	601020	141472	000000	101017	133464
- 7t	77777	1751 DC	2≥7677	17776	621656	141472	000000	301017	137444
- 16	~ ~ 7777	171000	637572	1777-0	000750	137473	300021	272757	141445
-11.	527777	177757	137234	177775	LC021C	257251	LLCCIC	175715	076427
-112	577777	.774∟€	037654	177770	LBG21C	657051	LLCC10	015000	~ 744 °
-112	::7777	1774US	J37~54	1 7777ና	000176	247451	066617	005170	C 35643
-128	r-7777	177777	137554	357025	000000	[37421	060000	105066	C37437
-173	-45	137737	637564	000000	อดออจรัด	337421	ემნნში	მომოსმ	^37437
-1^t	040000	.00000	237854	500000	882288	237421	000000	222766	537427

Two axis $\Delta x, \Delta y, \Delta z$ incrementally - 0 to 128 pulses and return to 0 again.

1	1	3							
9536	32758	1							
2	040000	000000	640086	000000	000000	040000	200001	ספרפים	C43387
4236	020040	000000	040000	300000	003239	040000	222888	201000	C 4C 30°
₹192	0407QG	000000	645656	000000	000000	040060	000035	bachaa	040001
12288	1339#3	000000	LADCOR	000000	000000	040000	CCGCCC	00000	C#60fc
15384	540000	000000	C480GC	200300	000000	54733 6	060660	000700	04000^
2748C	942996	000000	040030	000000	0.00000	040000	000000	000000	040061
24576	ոգրըըը	000000	646660	000000	000000	00000	050000	00000	T 4 CO CC
28672	040000	000000	040366	000000	000000	040000	000000	ספייטפט	040007
32758	040000	000000	040030	300000	000000	0400u	000000	000160	040000
ცლიგ	837489	025245	035217	03000	000000	049000	003777	175573	1 50 34 5
£192	037002	124477	C3F241	030033	000000	540005	GC7725	C73552	133027
12238	735315	G67727	077357	300030	000000	041000	013551	071125	136127
16384	034052	050014	175554	965669	000000	040000	017256	164164	191447
2ግፋጸር	031745	150733	0645C6	320026	000000	040000	822567	035725	C43374
24576	G 2 7 3 2 3	176514	172114	ימנוננים	paoros	040033	025637	174055	132257
-16384	233425	050014	175747	abbabh	000000	040000	017255	154164	171357
-27486	235615	E57727	877536	530370	00000	047333	C13551	021125	130000
-24575	277002	124477	635440	630320	999999	640006	OC 7725	073552	1 32 64 5
-23572	337607	025245	€35434	200031	00000	046596	CC 3772	125573	153137
-32768	049889	900000	040331	999999	000000	04 2000	000000	כפיספם	041461
-4096	240000	. 900000	G48331	000000	000000	040000	000000	000100	041461
- 3192	04076C	200000	049C31	966666	000000	040000	660090	000100	041461
-17288	շերըը։	occcce	040031	COCCOL	200000	040000	cccccr	ברכייםנ	T41461
-16394	047000	000000	040331	000000	202000	049603	000000	ספרספס	C 41 461
~25480	848666	000000	04CJ31	933856	600000	040090	003037	000000	241461
-24576	223243	cccccr	046031	000000	COOCDC	847686	ccoecc	cccroo	E41461
-25672	040000	300300	040031	000000	r 00000	040000	000000	corpos	041461
-32768	r4003C	000000	649331	900997	000000	040000	000000	סטרטנים	C 41 461

Two axis x,y sequentially - 0 to 32,768 pulses and return to 0 again.

TABLE 5.2 (cont.)

ū	1	1							
0006	72765	ī							
ũ	040000	000000	040030	000000	000000	040000	200007	ספרפנים	54000-
4096	037600	325245	035227	000000	000000	040000	003772	125573	1 60 34 5
4132	037002	124477	G35241	360000	000000	049000	003777	073552	1 33022
11238	075615	267727	C72357	cacane	000000	040000	G135F1	651125	170127
15334	034052	050014	175554	200000	600000	049000	017255	154164	1-144-
23480	C31746	150733	D645D6	000000	000000	947990	022537	035725	~43374
2457E	027323	176814	172114	cacacc	C000G0	C4C00C	025637	174055	132252
23572	824406	013657	173402	336336	000000	040000	030437	C67710	046071
32768	321224	250037	135327	000000	300000	040000	032732	124436	343614
4236	C21117	C37211	172168	1755.0	C53432	027050	C32732	104436	C43614
3132	020501	616662	155114	173551	163439	166273	032732	174436	243614
12283	820055	622413	046370	171525	1 22024	125302	032732	124436	C 43614
16724	017130	121260	122723	167553	174637	032745	032732	124436	E43614
2043C	015012	163074	GC3417	185704	104453	100765	032737	124436	043614
24576	014515	621515	055525	164155	165634	142755	032732	124436	043514
28672	013057	047010	025557	162565	C73366	053514	G32732	124436	C43614
32753	011256	166324	124453	161347	004425	063060	032732	124436	343614
-45 36	013052	C47C1C	025600	167565	073366	053506	332732	174436	C 4 3 61 4
-8192	014515	C21615	CEESCO	164155	165634	142777	032732	124436	C43614
-12285	616913	163074	633461	165704	104453	101105	032732	124436	C 4 3 61 4
-15384	017130	121260	122776	167553	174637	033047	032732	124436	393614
-25480	030065	222413	C46372	171525	122024	126362	G32732	124436	C43614
-24576	020501	016652	156100	173561	163430	165366	032732	124436	C43614
-29672	021117	537211	172157	175660	C53432	027102	032732	124436	243614
-32766	C21224	050037	135555	CC C 6 0 C	000000	G4CC27	032732	124436	£43614
~4096	C24406	C1 3557	173560	000000	000000	040027	030437	067710	046051
-3132	027327	175514	172433	000000	000000	040027	025637	174955	132151
~122ª8	945 [53	150733	LE5175	COCCED	COOCOC	040027	022562	035725	£433 C3
-15384	034252	252214	175151	000000	000000	040027	317256	154164	101235
-20480	035615	267727	073003	000000	000000	040027	013551	001125	127657
-24576	037002	124477	036623	000000	000000	G40027	GC7725	C73552	132500
-23672	237500	025245	035553	660000	000000	040027	003772	125673	157735
-32766	349999	202220	040163	000000	000000	040027	000000	201000	041255

Two axis, y,z sequentially - 0 to 32,768 pulses and return to 0 again.

1	r	1							
4096	32762	1							
e	040000	ממכטסט	240000	000000	מסטרחנ	040000	050101	ერერვი	n ungno
4036	94980r	GCCGGC	64036h	900000	000000	040000	cccoor	בפרכיים	դեն շրո 4. Մ
3132	ពុធពិច្ចព្	300330	£40000	000000	207000	347233	000001	077707	795367
12299	ייש מסמר	COTOD	L46151	000000	00000	547733	300000	כפרפרם	74237
16324	ლოინცი	iccoor	C4C2CC	30,000	CCOCFC	047000	CLCCGr	chanca	กรองกา
20430	04 DQCC	gemean	Euroar	0.00000	000000	640003	cccoor	อกปกอก	- 45350-
24576	040000	conson	040000	200800	000006	047506	20000	cterce	racer
23672	040000	860090	640000	000000	000000	94°906	000000	000000	F 403F-
32768	040000	000000	640000	000000	000000	040006	eccepe	enches	racers
4096	037600	025245	C35223	174005	C52104	117367	000000	000700	TACEST
8192	037902	124477	935227	170052	104225	144711	000000	010101	14001
12288	03561/5	C67727	C72344	164216	176652	147685	000000	charan	145561
16384	034052	05CŒ14	175535	160521	013613	176300	000000	อดดาดอ	640000
20480	031746	150733	G64465	155215	142053	034345	000000	סטרטטט	140061
24576	027323	176614	172671	152140	C03722	145471	000000	GCCCCG	C400PC
-16384	034052	G50014	175737	160521	013613	175374	000000	000000	C408C7
-20430	335615 /	057727	677804	164216	176652	147743	000000	000000	940367
-24576	037002	124477	C3F447	170052	164775	145575	סכסתרת	pronec	74CCC7
-23672	037600	C25245	035414	174005	052104	117512	000000	anchaa	740077
-32768	7300#2	000001	040644	000000	CODDCC	C3F213	ccoanc	esched	C466C C
-4096	640000	000000	040044	000000	000000	035213	000000	aganga	C40261
-5192	046060	ocoacr	040044	CDCCCC	000000	C 4 = 2 1 3	000000	change	140001
-12733	640 <u>3</u> 04	соласл	643944	000000	ออกกอย	D33213	203090	adahan	148361
-16394	246667	199783	546644	600666	בפפרחנ	079210	פננרני	areret	rucern
-20430	შ ოცეტებ	020201	340344	000000	000000	035215	ออธิธิสา	<u> </u>	14000
-24576	640066	060660	C40044	000000	CBOOGG	036213	GCBBCC	סרכינו	Ր 46ე Ր Ր
-28872	04000 0	000000	040044	000000	ومومود	035213	רמסטטט	მიიომნ	C43601
-32766	64000	בכככטי	C40044	600000	000000	036213	ceccar	อาการธ	C488CC

Two axis x,z sequentially - 0 to 32,768 pulses and return to 0 again.

TABLE 5.2 (cont.)

1	1	I							
L ^0	32768	1							
ε	C40CCC	CCCCGC	ር 4 ሮ ሮ G ሮ	000000	600000	045000	CCCCCC	פרברפפ	רְשְׁכָטַּרָי
uC⇒8	G40CCC	000000	040000	000000	C66666	CHCCGC	500000	<u> Ը</u> ოცონც	C400 mm
=192	040000	000000	646666	600000	000000	04 C C C C	cccccr	0,520	040017
17233	048257	205000	640660	000000	000000	348836	ისიიბი	00000	04630
15734	040000	000000	840937	0.00000	000000	34200 3	200000	000000	ቦ 4C ጋዮ′
22496	048000	000000	640000	600030	000000	Ე 4900Ს	000000	005700	940 JPA
24575	040000	000000	649336	000000	000000	241202	000000	000000	C400C
23572	040000	000000	648938	000000	000000	640000	909030	סמיסים	C48301
32758	C400C0	000000	048089	000000	000000	04029 0	273686	000000	040000
4006	037600	E25245	C3#227	000000	000000	647286	CC3772	175473	166345
-192	F370E2	124477	036241	000000	098889	040686	CC7725	073552	133023
1-298	035615	C67727	C72357	000000	COOOCC	047006	C13561	001125	1,50152
13384	034052	050014	175554	000000	000000	949030	D17256	164164	10144_
23480	031746	150733	D64506	000000	000000	049930	022567	035725	943374
24576	027323	176514	172114	000000	000000	040303	025637	174055	1 32 25 7
-16384	034052	050014	176151	000000	000000	040027	017255	154154	121235
-20490	335515	067727	373033	000000	000000	845627	013561	001125	127657
-24576	037002	124477	035623	000000	000000	049027	007725	073552	1 32 501
-25672	CZ7EGC	025245	L35553	033383	000003	640027	CC3772	125973	15773=
-12768	Croccr	200500	C40163	233383	200000	040027	CCOCCC	00000	C41255
-4-05	740CC0	000000	040163	000000	666666	C4CC27	000000	chance	C4125*
-3192	333943	222233	040163	233303	000000	C4CG27	55 666 0	occhoc	C4125 =
-12288	190000	200000	G4C163	606068	000000	C4C627	CCCCOC	ממרממ	C4125°
-16394	CABECE	ECECGC	C40163	000000	00000	646627	000000	00000	C4125°
-27430	240000	000000	040163	000000	000000	3477 27	303000	300033	~41 ZS~
-24576	242300	696366	C4C163	000000	000000	040027	000000	מפרסתם	C 41 25 5
-23672	540000	820000	J47163	000000	500006	J49027	300000	שמרסרפ	C 41 25°
-32766	0.0000	cccccc	040163	COCCCO	000000	C4CG27	000000	000700	[4125°

Three axis x,y,z sequentially - 0 to 32,768 pulses and return to 0 again.

1	1	r							
4 G 3 B	1	32768							
G	040900	000000	040300	000000	000000	040000	مومممم	00000	D400gr
4096	037500	062451	006016	000177	121314	047357	003764	155927	173570
4096	037600	052476	153331	000177	1 21314	047357	003765	055P30	1 30 74 1
3192	037005	067376	G63240	000772	1 20254	150745	007657	134273	102335
4192	0378α5	04765°	074437	000772	120254	150745	007653	032706	041664
17233	035632	166516	S17277	002145	024625	177341	013347	111422	021053
1,508	035632	137666	100545	CG 2 1 4 5	G24625	172041	013344	CC51G7	1474 67
15394	034124	G23505	070720	003653	173037	153720	C16545	144703	051427
16384	034123	165172	055642	003653	173037	153720	016546	035153	n 73 32 7
20480	032113	646642	147771	05664	160533	C16626	021375	666766	172775
20490	032112	175647	105725	005664	160533	015626	021375	153135	03151~
24576	02764C	067321	044715	010137	1 34555	012732	023575	157713	033125
24576	ግ2764 ሮ	017425	025375	010137	134555	012732	023576	D3741C	141577
2-672	02517C	185127	127435	012607	040163	J97237	025333	932763	71177 ت
23672	025170	112311	163765	012607	040163	007237	025303	174444	111425
32768	022375	153410	159573	015402	052652	177760 ,	026263	050721	052171
32766	022375	675641	16173F	015402	052652	17776C '	026263	115714	174447
-4096	C2517C	112311	153732	012=37	112771	172752	025303	057025	136267
-4096	[2517F	112311	167732	E12607	C40163	007260	025363	104044	111477
-1192	C2764C	017425	G25342	010140	004151	071275	023575	017111	<u> </u>
-3192	02764C	017425	025342	010137	1 34555	012554	023576	037410	141534
-12288	C32112	175647	105732	005665	C23526	171213	021375	137763	C251C2
-12298	°32112	175547	105732	005664	160533	015473	021375	153135	7 31 367
-15384	334123	155177	û5 55 27	003654	030354	075356	016545	025423	~4763~
-15394	034123	165172	066667	003653	173037	153560	016546	035153	^73244
-22488	035632	137606	130516	002145	053535	177642	313344	075°75	247345
-22480	035632	137606	100516	002145	024625	171736	013344	005107	14743!
-24576	037005	047650	074463	000772	1 40003	033424	007653	030 720	161345
-24576	037005	C47650	C74463	000772	120254	150575	007653	032756	041625
-29672	03750C	C57478	153311	000177	131267	007665	003765	054431	056102
-28672	ሮ፣75ፎሮ	C52476	157311	CGC177	121314	C472G3	003765	055730	1,6368
-32763	040300	000000	C375C7	000000	000000	237675	000000	GDODOG	C42717
-32768	040000	00030^	G37607	000000	000000	037675	000000	פפיכסס	C 42 71 7

Two axis $\Delta x, \Delta y$ incrementally - 0 to 32,768 pulses and return to 0 again. TABLE 5.2 (cont.)

С	1	, ı							
4096	í	32752							
7 C 5 C	040002	303335	849866	000000	000000	340000	000000	ספרבפס	040000
4096	037400	135147	121541	174013	0 22 3 50	104712	003765	055^30	1 36 21 4
4396	237490	125175	£67460	174012	123347	J22345	003765	055°30	1 30 21 4
9192	036012	137245	120273	170125	043504	176160	007653	032706	041163
9192	036012	117520	133456	170124	147457	117171	067653	032706	041163
12298	C33465	126324	160564	164434	066356	057443	C13344	005107	146735
12288	233465	277414	145345	164433	177203	031503	213344	003137	146735
15384	930250	611707	120+44	161232	C 33075	017135	015545	G35153	C 72673
16384	C30247	154364	126116	161231	152355	030656	016545	035153	0.72677
20486	024225	G36512	016777	156402	111071				
20480	024225	173516	170506	156402		105501	021375	153135	631137
24576	017500	105446	C33414	154202	040415	053250	021375	153135	031137
24576	01750G	337052	034373		020070	345234	G2357F	G3741C	141345
		037037		154201	160567	077514	023575	037410	141345
23672	012361		C47442	152474	145715	366255	025393	104444	111361
23572	012361	024623	136332	152474	1 20752	141777	025303	104444	111361
32768	CC4773	C52252	C73662	151514	137557	C25G42	026263	115714	124471
32768	004772	175533	140032	151514	115070	156064	025263	115714	124471
-4096	C1236C	152014	100323	152474	1 20752	147844	025303	131406	118354
-4296	C12361	224623	136376	152474	120752	142044	025307	154444	111443
-8132	017477	167455	C75757	154201	160567	077637	023576	076510	170235
-8132	917500	637052	034266	154201	160667	077637	023576	037410	141507
-12288	C24225	130522	171332	156402	C40415	C57406	021376	G23F10	155537
-12288	024225	173516	170277	156402	040415	053406	021375	153135	031278
-16384	C3J247	117047	152736	161231	152355	033736	016546	115~72	16653°
-16384	C30247	154364	126003	161231	152355	636736	C16546	C35153	C73C7#
-20490	033465	050504	044723	164433	177203	031575	G13344	C74762	117405
-2048C	033465	677414	145316	164433	1 77203	031575	013344	005137	147267
-24576	E76C12	C77771	152725	170124	147457	117242	007653	126733	061211
-24576	~ 036012	117520	133566	170124	147457	117242	007653	032706	C41477
-23672	037400	115222	C34532	174012	123347	022572	003765	154731	17323~
-28672	C2748C	125175	£67613	174C12	123347	022572	003765	055130	130611
-32768	037777	177777	137772	000000	000000	036571	000000	100000	04177c
-32758	040000	000000	637772	000000	000000	036571	000000	ממרטסט	C4177r

Two axis $\Delta y, \Delta z$ incrementally - 0 to 32,768 pulses and return to 0 again.

1	o	1							
4 A3	1	37772							
C	רשטרני	SECUSE	ርቁጥ ሂኖ	800L0	במפיהכ	145505	ceener	იივივე	ract 1
4339	237530	Le2451	375775	174717	J 2235L	1~4117	055177	121714	747355
→こ きゃ	777500	C52475	153215	174312	122747	145747	380177	121714	-47354
1 32	217775/	D6737=	253215	170125	643504	175354	000772	127254	156767
192	<i>רזץ~ר</i> ר	54765°	L 7441=	170124	145472	574106	828772	120254	1557F
15 39	775577	165715	17247	164434	0 F 5 3 F 5	255435	322145	374723	172757
12246	~35737	137335	107019	164433	172574	130311	032145	374525	172354
1.559	774174	J2230F	ב, הדם	161237	233275	215722	303657	173737	1 = 3 74 7
18284	74127	168177	006005	161231	142F25	20432	203657	173037	153767
77480	232113	049542	147725	156407	111271	174741	025654	150533	716557
174PC	E 32112	175647	15567	156452	C24643	046027	EE5664	160533	riesea
4576	G27340	237321	£48355	1542C2	020578	344525	019137	134 = 55	C12777
24575	027640	517425	025330	154201	140367	175157	013137	134555	12777
-4236	C25177	112311	157571	152474	073333	145333	212507	042163	227322
102	57545	317425	[~= 71	154201	16CF67	577151	C1C14°	CC4151	22 2 2 2 2 2
- 3 " 42	C7754C	017425	L 25 271	154201	140367	135223	010137	134555	F12514
-12236	237117	175547	125563	156402	J40415	352537	005665	023525	131245
-12-88	500112	175647	105663	1564C2	C24543	646356	GG5664	162533	£1657f
-15334	2412	155177	· .5547	161231	152355`	J37102	003654	073754	~ 36401
~16330	7.41.22	155177	J56543	161231	142575	274466	0°3653	173~37	15361-
-11-402	[75=77	137525	120054	164433	177253	537656	CL214 F	C53535	177685
-5543I	55	137505	160454	164433	17267.	130273	032145	074525	171751
-24575	_ 1100E	047337	574±30	170124	147457	115352	660777	140703	733447
-24 = 76	037cc-	C4753°	C7443^	170124	145472	こうにつフィ	CCG777	170754	150614
-79572	7777	C57475	153.55	174012	123347	001512	300177	131757	775 377
- 23 - 72	323370	C5.7477	153655	174312	122747	147335	308177	171714	747211
-1:766	£40000	000000	C 77577	COCCAA	COCCTL	5747CL	SESSEC	CCLTCC	~7766F
-27753	745000	מכבספר	J7577	מכמפרים	00000	314733	acacer	ตถะกบต	77661

Two axis $\Delta x, \Delta z$ incrementally - 0 to 32,768 pulses and return to 0 again. TABLE 5.2 (cont.)

			κ.						
1	1	ī							
4006	1	37762							
C	CAPCCP	CCCCCC	0.40000	CDBBCC	coocoo	547566	CCOCCC	00000	ር 4 ር ዐ ቦ ጉ
4,96	C374C1	E17531	143232	174217	16627C	157502	664157	CC2714	T106 CE
4796	B374C1	307173	037451	174217	166270	157502	204137	101316	C37537
4036	037403	177532	. 115160	174217	067266	150455	064157	171715	כ3753 ס
3192	036020	622312	172754	171167	041732	846942	010570	135714	147255
-172	036020	SC 02 5 3 1	GC4273	171167	041732	045042	316571	071754	- 172327
3192	036017	163237	C14117	171166	145672	062002	010571	031254	17237~
12275	033520	934255	631373	166777	062164	125334	015260	114276	156765
19298	C3352C	CC1314	111036	166777	C62164	125334	G15261	GF 3537	C14357
12288	033517	157312	166147	166776	172724	144505	015261	003537	C14357
18384	030372	020225	C35413	165535	133633	C25555	G2165C	C6744C	16756~
10384	030371	154503	175326	165535	133633	025555	C2165F	150424	184517
16784	030371	127777	BC4537	185535	C52647	121053	G2165C	150424	164517
204FC	C24531	115442	147551	165261	130765	C63547	G25765	GC5*22	£42574
20430	· C24531	341470	053422	185261	130765	053547	025765	055505	C 21 727
20430	024531	C14233	074112	165261	057503	305624	025765	856585	0 21 72 7
24576	020311	151363	024561	166003	055677	067767	031463	033564	027061
24576	020311	866214	274165	166003	055677	357757	031463	074567	966661
24576	023311	342222	157142	166003	G15054	137331	031463	874587	066661
28672	013551	017430	U23745	167532	170306	172664	034414	051971	171557
28672	613660	126377	032628	167502	170306	172654	C34414	11CF33	1376 E 5
28872	013660	105684	163073	167502	140545	136460	C34414	11CF33	1376 DF
32768	CC7174	035513	C722CC	172111	116341 .	C36764	C3647?	171110	153037
32758	557177	140026	011367	172111	116341	C3F764	C3547?	177566	151577
37768	CC7173	124551	C277C1	172111	C77751	151665	C3E47.7	137566	151077
-4796	C13= F "	014553	050222	167503	C31577	000652	634414	1:1166	C675F4
-4096	C1366^	105604	163035	167503	G31577	800652	634414	131425	3 4 5 2 P 4
-4[26	C1366C	105604	163035	167502	140545	136371	634414	110433	13755~
192	256317	157053	C65153	166003	100223	154447	031463	181722	1726 CC
-3132	023311	342222	157175	166003	100223	154447	C31463	170566	151307
-3132	020311	342222	157176	166053	015054	137237	031463	374937	n 56 agn
-12293	ウラリニマン	148263	C1 25 21	165261	1 3 3 4 5 5	179446	025765	155723	153275
-12288	224531	314233	074186	165261	133455	F70440	025765	104042	676511
-12233	024531	014233	074105	165261	057503	005571	G25765	056505	021671
-15384	030371	264254	130557	165535	116371	066121	021651	055115	CC 7555
-16384	F72371	127777	CC4121	165535	116 771	066121	G2165C	175131	173302
-15384	C2531	127777	CC4121	165535	C52647	120343	021650	150424	164547
-20486	C33517	12455C	C23641	166777	C25466	175243	015261	115~66	100001
-2C48C	C33517	157312	186402	186777	C25466	175243	015251	625540	173714
-27480	033517	157312	166402	166776	172729	143744	015261	Dr3#37	C14331
-24576	076017	141624	CC 266 I	171166	167254	161543	010571	142736	152134
-24576	735717	163207	C14516	171166	167254	161543	010571	046577	535161
-24576	275017	163207	014516	171166	145672	051357	010571	031754	172291
-28672	037462	16727?	175000	174217	077625	152334	J0416C	307561	C 3735=
-23672	037490	177632	115540	174217	077625	162334	004157	110557	0 50 24 ^
-28572	037400	177632	115540	174217	067266	150140	004157	101316	037353
-32768	837777	177777	148211	000000	000000	037025	000000	100730	r 37132
-32768	240000	000000	C4C211	000000	000000	037025	222222	פרכינט	C37137
-32768	040000	000000	C4C211	cocace	000000	037025	000000	פתביבב	C37132

Three axis $\Delta x, \Delta y, \Delta z$ incrementally - 0 to 32,768 pulses and return to 0 again.

TABLE 5.2 (cont.)

1	1	3							
ī	i	´ 9	1						
ō	040000	000000	១५០១០០	σορορο	000000	040000	000001	פסניטטט	040000
ı۱	037777	177777	140000	000000	000000	040000	peggan	100100	037777
1.5	037777	177777	040000	177777	100000	040001	200000	100700	n37777
2,	037777	177777	040000	- 177777	100001	040001	יוססססס	100001	037775
2,	037777	177775	137776	177777	100001	040001	000001	000001	C37771
2.	037777	177774	040000	177777	000001	040007	000001	000001	037771
3	n37777	177774	040000	177777	000003	040013	000001	000003	037765
3	037777	177771	137772	177777	000003	040013	000001	100003	E37752
3	037777	177767	040000	177776	100003	040032	000001	100003	F37752
4	037777	177767	040000	177776	100006	040042	100000	100706	037740
4	037777	177763	137764	177776	100006	040042	000005	000006	D37712
4	037777	177760	040000	177776	000006	040076	000002	000706	037712
5	037777	177760	040000	177776	000012	040116	000005	000012	037672
5	D37777	177753	137754	177776	000012	040116	000002	100012	C37625
5	037777	177747	040000	177775	100012	040173	000007	100712	037625
ร์	03777 7 7	177747	040000	177775	100017	040223	000002	100017	N37573
6	037777	1777:41	137742	177775	100017	040223	000003	000017	837503
6	037777	177734	040000	177775	000017	040325	5000003	000017	C375 07
7	037777	177734	040000	177775	000025	040371	000003	000025	037437
i	037777	177725	137726	177775	000025	040371	000003	100725	037320
7	037777	177717	040000	177774	100025	G40524	000003	100025	r3732r
8	037777	177717	040000	177774	100034	040604	000003	100734	037236
8	037777	177707	137710	177774	100034	040604	000004	000034	037064
8	037777	177700	040030	177774	800034	040774	000004	000034	037064
9	037777	177700	040000	177774	000044	041074	000004	ըորուկ	D 36 764
-1	77777	177780	040008	177774	000034	040774	000004	000034	037064
-2 -	037777	177707	137710	177774	100034	040603	000004	000034	037064
-2	037777	177717	040000	177774	100034	040603	200000	100034	937235
-2	77777	177717	040000	177774	100025	040521	000003	100025	037315
-3	037777	177725	137726	177775	000025	040365	200000	100025	C37315
- 3	037777	177734	040000	177775	000025	040365	000003	000025	037433
-3	037777	177734	040000	177775	000017	040321	000003	000017	C37477
-4	037777	177741	137742	177775	100017	040216	000007	000017	r37477
-4	037777	177747	040000	177775	100017	040216	0000022	100017	037566
- 4	037777	177747	040000	177775	100012	040154	000007	100712	C37616
-5	037777	177753	137754	177776	000012	040186	000002	100712	237616
-5	D37777	177760	040000	177776	000012	040106	000002	000012	r37667
-5	037777	177760	040000	177776	000006	040066	000002	000005	037702
- š	D37777	177763	137764	177776	100006	040031	000002	פמימסם	037702
-š	037777	177767	040000	177776	100006	040031	100000	100006	C37727
- 6	037777	177757	040000	177776	100003	040017	000001	100003	r \$ 7 73 7
- 7	637777	177771	137772	177777	000003	037777	000001	100003	E37737
-7	037777	177774	040000	177777	000003	037777	000001	000003	037751
- 7	037777	177774	040000	177777	000001	037773	000001	000001	037755
-8	037777	177775	137776	177777	100001	037764	000001	000001	037755
-8	037777	177777	040000	177777	100001	037764	000000	100001	037760
-8	037777	177777	040000	177777	100000	037762	000000	100000	D37760
~9	G37777	177777	140000	000000	000000	037760	000000	100000	037760
-9	040000	000000	040000	000000	000000	037760	000000	000000	037760
_	0.75000	00000	0.000						

Three axis Δy , Δz , Δx incrementally - 0 to 8 pulses and return to 0 again.

TABLE 5.2 (cont.)

	_								
1	1	1	` ,						
1	1	, 9	1 040000	<u> </u>	990000	,646666	900000	000000	(400 Bn
D	090000	000000	140000	177777	100000	940000	000000	00000	សត្ថិច១ ១១
I	037777	דדדדו	140000	177777	100000	040000	000000	ըլըորյ	C480 DP
2	037777	177777		177777	100000	040000	oppoor	100001	037776
2	037777	177777	037776	177.777	000000	040003	000000	100001	C3777F
2	037777	177775	137776		000001	040003	000000	100003	237774
3	037777	177775	137776	177777 177777	100000	040007	000001	000003	ฮ์ 37765
3	037777	177774	037770		100001	040021	000001	proros	P37764
3	037777	177)771	137772	177775	100001	040031	000001	902206	n 37 761
4	037777	177771	137772	177776	100003	040031	000001	100706	837741
4	037777	177767	037756	177775	000003	040056	000001	100006	n 37 74 1
4	037777	177763	137764	177776	000006	040036	000001	100712	337727
5	037777	177763	137764	177776	000006	040076	000003	000712	037672
5	037777	177760	037740	177776	1 0000E	0490142	000003	010112	037677
5	037777	177753	137754	177775		040172	000002	000017	r3765°
ε	037777	177753	137754	177775	100012	040172	000005	100717	737574
6	037777	177747	037716	177775	100012	040172	000005	100017	C37574
6	037777	177741	137742	177775	000012	040325	000002	100025	C37542
7	037777	177741	137742	177775	000017	040325	000003	000125	037437
7	037777	177734	037670	177775	000017		000003	000025	r37437
7	037N77	177725	137726	177774	100017	040443	000003	0000734	037373
8	037777	177725	137726	177774	100025	D40523	000003	100034	C37237
8	C37777	177717	037636	177774	100025	040523	000003	100034	037237
8	037777	1777707	137710	177774	000025	040674	000003	100044	037155
9	037777	177707	137710	177774	000034	040774	000004	600044	036764
9	037777	177700	037600	177774 -		040774		100744	037154
- 1	037777	177707	137710	117774	000034	040774	000003 ≈33030	100034	r37234
-1	537777	177707	137710	177774	000025	040674		100034	037234
-2	037777	177717	037636	177774	100025	040522	000003	000034	C37367
- 2	037777	177725	137726	177774	100025	040522	000003	000025	C37433
-2	037777	177725	137726	177779	100017	640440	000003	-	937433
-3	037777	177734	037670	177775	000017	040321	000003	000°25 100°25	C37535
-3	037777	177741	137742	177775	000017	040321	000003	_	037565
-3	037777	177741	137742	177775	000012	040255	000007	100717	(37565
-4	637777	177747	037716	177775	100012	040165	000002	106717	337642
- 4	037777	177753	137754	177775	100012	040165	000002	000017	C3766°
-4	C377177	177753	137754	177775	100006	040133	000002	000012	037662
- 5	037777	177760	037740	177716	800000	040066	000002	000712	-
-5	037777	177763	137764	177776	000006	040066	100000	100712	137716 137726
-5	C37777	177763	137754	17 7776	000003	040046	000001	100.06	-
-6	037777	177767	037756	177776	100003	040820	ינפסססס	100706	037726
-6	ל ליל לבם ל ליל לבם	177773	137772	177776	100003	040020	000001	800006	r37745
-6	037777	177771	137777	1777.76	100001	040006	000001	000703	037751
-7	237777	177774	G3777C	1771777	000001	037773	000001	660783	£37751
- 7	037777	177775	137776	177777	000001	037773	200000	100703	037757
- <i>1</i>	037777	177775	137776	177777	000000	037767	700000	100701	937757
	037777	177777	037776	177777	100660	Д37763	000000	100001	r37757
-8		177777	140000	177777	100000	037763	000000	000001	037767
- 8	037777	177777	140000	177777	100000	037761	000000	00000	037767
- 8	037777	000000	040000	00000	000000	037760	72000	occrso	037760
-9	0.00000	000000	5,555						

Three axis Δz , Δx , Δy incrementally - 0 to 8 pulses and return to 0 again.

TABLE 5.2 (cont.)

	1`	1							
1	1	32769	1						
4396 C	C480CO	000000	£4000Ĉ	600000	309000	040000	ccccc	Cr0r00	C4000C
4398	037401	017531	143233	174217	166270	157502	064157	002714	816606
4536	0374C1	607173	C 3 7 4 G 1	174217	166270	157502	CC4157	101716	C37532
4036	037400	177632	115160	174217	067266	150455	004157	101716	037532
3192	036656	035515	172764	171157	D41732	646642`	C1057P	135714	147255
41 72	036020	000631	624273	171167	041732	045042	013571	031754	1 72 32 7
3192	036017	163207	G14117	171166	145672	862892	010571	G31754	17232
12288	C3352C	C34C5F	031073	166777	C62164	125334	015260	114776	156765
12288	033520	CC 1314	111036	166777	062164	125334	313281	gn 35 37	014357
12288	033517	157312	166147	166776	172724	144505	015261	003537	Γ14357
16384	030372	020225	C35413	165535	133633	025555	92155 ^{rr}	057443	157552
16384	030371	154563	175326	165535	133633	C25555	021650	150424	16451?
16384	030371	127777	CC4637	165535	C52647	121053	02165C	156424	164517
20480	024531	115442	147551	165261	130765	063547	025755	22,520	542574
20486	C24531	C41470	063422	165261	130765	063547	025765	056505	Γ21727
254PC	C24531	C14233	674112	165251	057503	605624	025765	056565	521777
24576	020311	151363	024561	166003	055677	067767	031457	033564	527061 556661
24576	C20311	C66214	D74166	166003	C55677	067767	C31463	C74°C7	[5656]
24576	C20311	642222	167142	166003	C15054	137331	031467	C74°C7	
23672	013551	61 74 35	023745	167502	170306	172554	034414	061771	171557
28672	C1366C	126377	032026	16 <i>7'</i> 502	170306	172664	C3441#	110533	1376 CF 137605
23672	013660	105604	163073	167502	140545	136460	234414	110533	
32768	0071/74	635513	072200	172111	116341	036764	036472	121110	153037 151077
3775:	167173	140326	011367	172111	116341	035764	035477	137500	151977
3275=	007173	124551	027731	172111	077751	151665	036472	137500 031517	C71344
-4236	013657	102727	C50361	167503	67367C	, 153263	034415	001757	172434
-459=	013557	173761	104057	167503	073070	153253	034415	161166	r6756?
-4096	013557	173761	104057	167503	002036	170116	C34414 O31464	045135	313415
-3192	020310	Q4 7711	151327	166003	122552	031152	C31464	CE5714	C1E427
-8192	020317	133362	C250GC	166503	122552	C31152	C31464	161,55	172577
192	020310	122662	025000	166003	037402	642313 075242	025765	054741	114751
-12233	024530	037346	151551	165261	1 36150 136150	075242	025766	092560	14266
-12288	52453C	112053	030373	165261	062174	115136	025755	155723	163224
-12233	024530	11 3023	839373	165261	101131	123035	021651	163504	104610
-16384	030370	174024	016220	165535	101131	123035	021651	102522	051014
-16394	030371	637547	104547	165535	035406	142076	D21651	056115	297554
-15384	030371	037547	104647	165535 166776	170773	021731	015262	D26741	123327
-2048C	033517	050002	022311	166776	170773	021731	015251	137092	150557
-20480	033517	102546	007555 007555	166775	136227	145726	015261	115000	190901
-2048E	C33517	102546	D3D346	171166	114601	017037	010572	054421	001135
-24576	036017	102515 124201	06535C	171166	114601	G17C37	G18571	140761	152117
-24576	C 76017 C 76017	124201	C6535C	171166	C73215	C73517	010571	142736	162135
-24576		147370	140000	174217	011164	042215	00415°	115724	15470°
-23672	037400 037400	157731	C75447	174217	C11164	042215	004160	017723	C25355
-28672	037400 037400	157731	075447	174217	600624	013111	CC416C	007561	C3736F
-28672		177775	140206	177777	100001	037032	1100000	000001	777137
-32755 -32755	237777 237777	177777	646516	177777	100001	277032	200007	170701	C37133
-32768	277777	177777	249210	177777	186686	037039	080007	נפרפרו	251125
-32769	031777	177777	140210	000000	000000	C37C26	000000	126,66	C37137
-32763	040000	000000	640210	000000	000000	037026	000000	פסייםסס	22123
-2.05	2.3000								

Three axis Δy , Δz , Δx incrementally - 0 to 32,768 pulses and return to 0 again.

1	1	1							
4396	1	32769	1						
C	00000	000000	040000	000000	000000	090040	ספטרסר	000000	C408 Fr
4396	037401	02 70 71	119261	174217	155732	157355	004156	103311	143021
4895	N37401	016534	002434	174217	155732	167365	0[4157	002314	010645
¤	037461	007173	037317	174217	C56730	134436	004147	002714	P10646
8192	036020	037634	035727	171167	020350	171271	010570	041154	071217
8192	0236620	016253	G37337	171167	620350	171221	010570	135714	147321
3192	036020	000631	004223	171166	124310	152115	010570	135714	147321
12288	033520	056057	062357	166777	027423	115665	015267	D25°36	055361
12288	033520	02 33 16	121016	166777	027423	116666	015260	114276	156756
12288	233520	001314	110625	155776	140163	272333	015260	114276	156755
16384	030372	6441731	173654	165535	070112	073330	B2165C	006454	121463
16394	030372	001211	075537	165535	070112	073330	021657	057440	157545
16384	030371	154503	174777	165535	C07126	115414	GZ1650	C6744C	16754F
20430	024531	142577	143646	165261	055013	076473	G25764	134737	010554
20480	024531	066726	002265	165261	055013	076473	0257654	005322	042401
20480	024531	041470	063031	165261	663536	146055	025765	005*22	[424[]
24576	020311	175354	176157	166002	172531	024567	031467	173440	117007
24576	020311	112206	147232	166002	172531	024567	031462	033664	r265 7 2
24576	020311	066214	073671	166002	131706	074144	031463	033564	026577
28672	013661	040222	175246	167502	077256	051726	034419	031727	16166°
28572	013660	147172	062625	167502	077256	051726	034414	051771	171275
28672	013660	126377	C31617	167502	047514	154136	034414	061771	171275
32768	007174	051271	011163	172111	D21154	010755	036472	102520	125205
32768	007173	154103	165332	172111	D21154	010755	D36472	121115	152602
32768	007173	140326	011272	172111	C02564	C74324	C36472	171110	1526 C2
-4396	013657	123521	073700	167503	002036	179616	034415	001757	172327
-4096	013660	014553	050077	167503	002036	170616	G34414	152220	032033
-4096	013867	014553	050077	167502	111005	064750	034414	131425	1 45075
-8192	620310	073703	112771	166003	037402	043077	031464	005714	C10441
-8192	020310	157253	065000	166003	037402	043077	031463	144472	135467
-8192	029310	157353	065000	166002	154232	155704	031463	120500	151315
-12286	02453C	664-304	056265	165261	062174	115625	G2576F	002560	142767
-12298	Π24530	140260	012345	165261	062174	115625	025775	131277	116203
-12288	024530	140260	012345	165261	C06221	060254	025765	154742	Luee5u
-16384	030371	020532	003627	165935	035406	142665	021651	192522	251145
-16384	030371	064254	130311	165535	035406	142665	021651	021637	144137
-16384	030371	064254	130311	165534	171664	123674	821650	175131	173432
-20430	033517	07 2005	014450	166776	136227	146406	015251	137002	1 50 752
-20480	033517	124550	023216	166776	136227	146406	015761	047543	1322 15
-20480	033517	124550	G23216	166776	103465	051101	015261	075540	174127
-24576	036017	120240	135232	171166	073215	073755	010571	160761	152355
-24576	036017	141624	002135	171166	073215	073755	010571	064322	070272
-24576	036017	141624	002135	171166	051532	140535	010571	046577	735347
-28672	037400	156733	034610	174217	000624	013211	004167	017223	, 280 Lz
-28672	037400	167272	174254	174217	000624	013211	004157	120221	757555
-28672	037400	167272	174254	174216	170264	162111	004157	110657	r506FF
-32768	037777	177777	037523	177777	100000	037147	000000	100701	037657
-32768	037777	177777	137525	177777	100000	D37147	000000	000000	C37657
-32768	037777	177777	137525	17777	100000	037145	000000	00000	r3765*
-32769	040000	000000	037525	000000	000000	037144	000000	ספרפפפ	737653

Three axis Δz , Δx , Δy incrementally - 0 to 32,768 pulses and return to 0 again.

TABLE 5.2 (cont.)

YOT									
77 etta 70 AT	10:49:07 4254 /	THE CALLS	ECTOR 1109	-0313					
512 0 512 1024 -512 -1024	1 1924 04000 037776 937770 037775 040000	000000 000000 000002 000032 000032 000000	10 340000 165200 165024 165163 037670	000000 000000 000000 000000	000000 00000 00000 00000 00000	040003 340000 640000 947636 949295	880097 088377 088777 086377 086887	010100 176525 15525 176525 000100	04000° 11375° °27743 11463° 041541
C 512 1774 -512 -1924	040000 037775 077770 037776 040000	Corcor 300337 303957 LCCCC7 000300	C3767C 165365 164357 1C5C45 G37551	000000 000000 000000 000000	000000 000000 000000 000000 000000	047500 04000 04000 04000 04000	E00000 CC0377 CC0777 CC0377 Oc0000	000400 176525 166753 176525 003100	C41541 115511 731477 116371 C43300
512 1024 -312 -1024	040FCF 037775 037770 037775 FLECOE	CCCGGC GCGGGG GCGGGG GCGGGG	C37551 154725 154534 154711 C37444	900303 900000 900000 930000 730000	00000 00000 00000 00000	847808 047000 047000 040000	000000 000377 000777 000377 000000	00000 176525 155753 176525 00000	043300 117245 033234 120125 045037
512 1024 -512 -1124	148800 537775 537775 637775 646116	50000n 050007 150U57 030007 55000n	037444 1546C1 154371 154555 637532	00000n 000000 000000 530380 000000	30088 30308 30308 00308 333303	04 0000 34 0000 64 6606 34 3033 64 6602	000001 000377 000377 000000	070000 176925 165753 175925 070000	C 45037 121364 C34772 121664 C46574
C J12 1724 -,12 -1774	040000 037778 037777 037777	LECTION LOCAT LOCA	637332 154453 154217 164434 C37217	000000 000000 000000 000000 000000	000001 000001 000001 000000	047603 040003 047701 047600 048777	000000 000377 000377 000377	000050 176525 165753 176525 919760	C 46574 1 22535 C 36522 1 2341 C 50 327

Single Axis - Runs 1-5

TABLE 5.3
Oscillatory Runs-Ten Cycles O to 1024
Pulses and Return to O Again

12 127- - 12 -1224	(4000 03737 73737 03737 04000	500000 100000 100000 100000	C37217 164324 164055 16401C 037104	000000	100000 100000 100000 100000	646,00 14703, 646866 Jef886 346833	500000 300777 300777 400377 60000	676746 17:523 17:533 17:515 67:5783	050377 124777 746264 125167 052367
-12 12 12	07777. 07777. 077777 03777= 040000	LETCOR 000001 LETCO LETCOT 00001	C27104 154177 1537_7 164136 C36776	00000 00000 00000 00000 00000	, 100000 100000 100000 100000	040000 040000 040000 040000 640000	200777 200777 200377 200377 200667	001000 176505 155052 175925 004040	CR2000 176327 142000 176700 183616
5 -12 1.74 -312 -1774	649086 	000000 000000 000000 0000000	036776 134051 163547 164037 030671	000000 000000 000000 000000	corpo conut coupo fouco puedo:	34 1900 14 7000 14 7000 14 7000 64 7000	000000 000377 000777 000377 0007 0	000000 176925 176953 176925 000000	2 5 3 51 5 1 7 7 55 6 1 4 2 5 7 7 1 7 4 7 7 1 7 5 2 4 7
0 512 1024 -512 -1024	040001 037776 037777 037777 040000	007000 007007 007007 007000	C36671 113723 167377 117707 C36555	000000 000000 000000 000000	, 200000 200000 200001 200011 000000	047303 _#***03 _4*666 _4666 04730	060607 060377 060777 060377 000000	833782 176°25 165°53 176°25 090°03	- 65345 171373 CUSZFF 132167 067075
0 117 1-24 - 112 -1734	CLRCCL 37775 57775 57775 646555	Foncon Johann Johann Johann	1.7077 1.7077 1.7027 1.7027	000000 000000 000000 000000	80000 60000 60000 60000	34,030 04,033 04,020 64,020 64,020 64,020	ELCCCT 363377 60377 60377 60360	201760 175525 163753 175525 37J788	(57675 133037 047611 133717 050674

Single Axis - Runs 6-10

12 12 12 12 12 12 17 17 17 17 17 17 17 17 17 17 17 17 17	1 1074 040099 037776 037779 037776 037776 037777 037776 040000	1 0000000 0000000 0000000 0000000 000000	10 547300 16524 111350 104637 11177 164711 135517 677555	000000 000000 000000 177400 177400 000000 000000	00000C C0C00G 000000 C21251 052521 C21251 00000 C00000 C00000	647000 040000 040056 164056 050415 164776 037124 037124	00.0000 6.00377 880777 6.00777 6.00777 00.0777 00.03377 6.000000	000000 176525 165253 165253 165253 165253 165253 175253 0000000	740507 113707 727743 727743 727743 727743 727743 114637 741544
0 1-1- -14 1224 12 -1024 112 -1024	043330 037777 317777 317777 337760 037766 717766 717775 040080	007307 .07707 .07757 .007107 .007525 .007157 .007037 .007037	2373 25 1 r 4 7 4 7 1 3 4 2 7 4 1 11 2 7 7 1 3 4 1 3 4 1 1 1 1 1 C 2 1 5 4 4 2 7 1 7 4 9 2 5 2 7 3 2 1	393300 CBCCCC 3GC335 17743C 17743C 1774CC 9GC3C9 34C33CC CCLCCC	000000 CCCCC CC0000 C21251 052521 C21251 000000 U00000 LGCCCL	677124 C77124 J27124 157227 G47553 16*13C G75255 J37253 C75255	0:0000 0:0177 0:0177 0:0177 0:0177 0:00777 0:0377 0:0377	000707 176525 165753 165753 165753 165753 165753 175425 000000	C41544 11.517 131507 131507 131507 131507 131507 143377
1724 1724 112 1724 -512 -1724 -1724 -1734	043000 037710 037710 037766 037766 037766 037766 037767	730 M30 U00007 U000357 U00155 U00575 U00575 U00575 U00757 U00757	037521 1-4475 1-4314 410017 41405 117504 1-4175 45425 274	60030h 60030h 000000 177400 177000 17743h 600000 6000000 60000000	500000 100000 00000 021251 052521 021751 000000 0000000000000000000000000000	725253 C36253 C36253 162336 C46703 162256 176401 C76401 C76401	000000 600377 000777 000777 000777 000777 000377 000377	000700 176425 166753 166753 166763 166763 176425 00000	743377 117247 73237 732237 732237 73237 73237 120127 745047
512 1024 512 1024 - 512 - 1024 - 512 - 1024	04000r 037776 037776 037766 037766 037765 037776 037776	000000 000102 000001 000135 000135 000152 000052 100052	037105 164242 164732 110335 107564 117378 134112 036657	0-00000 000000 177400 177600 177600 000000 000000	000000 000000 000000 021251 052521 021251 000000 000000	035401 035401 035401 161466 046037 161406 034526 034526	000070 000377 000777 000777 000777 000777 000377	000000 176*25 165*53 165*53 165*53 165*53 176*25 000*00	045043 121006 C74771 034771 034771 C34771 C34771 121666
512 1724 512 1624 -512 -1624 -112 -1724	C40000 137776 027776 037766 037766 037766 037776 037776 037777	360 - 3 - egoco 2 - goco 52 - goco 62 - goco 6	035557 154000 167544 110044 10031 163426 153643 036426	360300 000000 000000 177430 177430 000000 000000 000000 Two Axis	050000 000000 000000 021251 052521 021251 000000 0000000 0000000000	074 5 2 5 074 5 2 5 074 5 2 6 160 5 2 0 045 1 7 3 160 5 4 0 037 6 5 3 037 6 5 3 037 6 5 3	000000 000377 000777 000777 000777 000777 000377 000377	000"00 176"25 165"53 165"53 165"53 165"53 165"53 176"25 0000"00	74660° 122537 136521 136521 136521 136521 12341° 150337

TABLE 5.3 (cont.)

0 510 1074 512 1024 -512 -1074 -712 -1024	040000 037776 037770 037766 037766 037766 037767 037777 040000	000007 000002 0000052 000105 000105 000105 000007 000007	0384 26 163533 163264 107562 107547 163151 1074 34 COFFEE	000000 CDC000 000000 177400 177400 00000 00000 00000	000000 000000 000000 021251 052521 021251 000000 000000	033653 033653 033653 157753 0575753 0575753 033C02 037C02 037C02	00000F 060377 000777 000777 000777 000777 000777 000377	0°0000 176525 165753 165753 165753 165753 165753 176725 00000	050333 174277 C40251 C40251 C40251 C40251 C40251 175157 C52077
112 1124 1124 1127 12 1	040000 037775 027777 037766 037766 037766 027777 037776 027777	600000 500000 60050 60050 600525 600052 600052 600000	036200 1-3273 - TUCT 137272 107465 107236 167696 147134 CEF754	000080 000000 000000 177400 177400 177400 000000 000000 000000000	000000 000000 00000 021251 052521 021251 000000 000000 000000	033092 033002 033002 157103 843461 157023 032130 032130 032130	GBBCGB GC3377 GCG777 GCG777 GCG777 GCG777 GCG777 GCG377 CCGCCCC	000100 176*25 165*53 165*753 165*753 165*753 165*753 176*25 50*000	05207n 1760Z5 0420C4 0420C4 042004 042004 0420C4 126707 053625
112 1726 112 1726 - 12 1726 - 1274	743000 677777 677767 677767 677767 677777 646667	550000 000000 000000 000135 000505 000000 000000	CUS754 167227 17526 127037 102175 105275 162416 1671 6 251340	333980 353378 353378 377438 177430 177430 660307 639837 600800	000000 000000 000000 000000 021251 052521 021251 000000 000000	237133 237130 277130 156233 042616 156153 031256 031256	000000 000377 000777 000777 000777 000777 000377	00000 176525 165753 165753 165753 165753 176725 071700	753625 127557 143537 143537 143537 143537 143537 171437 155356
11.1 11.1 11.2 11.2 11.2 -31.2 -17.2 -11.2	042900 01777 02777 027760 027760 02776 02777 027777	300001 400001 400101 400100 600100 600000 600000	035540 107077 167247 105020 1016507 105507 167136 157446 005314	000000 000000 177400 177400 177400 000000 0000000	000000 00000 00000 021251 052521 021251 00000 000000	031256 031256 031256 155354 041750 155304 070403	GEDGON 000377 600777 000777 000777 000777 000777	000000 176525 165753 165753 165753 165753 176725	755356 131372 F45251 F45255 F45256 F45256 C45256 132167 F57176
1776	747777 77777 777767 777767 777767 77777	10101 10101 000331 001331 001331 001331 001051	1.7.17 1.7.77 105235 105222 151664 152203 0:5061	000000 600000 177400 177400 177400 600000 600000	030035 CCLCCC G0003 C21251 C21251 CCCCC GGG073 COLCCC	377403 C77403 C77403 154512 C4512 154432 C27530 C27530	000000 000077 000777 000777 000777 000777 000777 000777	070°02 176°25 165°53 165°53 165°53 165°53 165°53 165°53	0.571 C= 1.7303 C= 7.4700 C= 7.4700 C= 7.470 C= 7.470 C= 7.470 C= 1.7371 7 C=064 C=

Two Axis - Runs 6-10 TABLE 5.3 (cont.)

1 512 512 1024 512 1024 512 1024 -012 -1024 -112 -1024 -112	1 1024 640000 040000 040000 037776 037776 037776 037776 040000 040000	1 000000 000000 000000 000000 000000 0000	10 040000 040000 165200 165200 1653024 1.1350 104520 111336, 164711 175050 037555 037555	COBBBC GOBBB GOBBB GDBBCB BOBBB BOBBB 1774CB BOBBBB GOBB GOBB GOBBB GOBB GOBB GOBB GOBBB GOBB GOBB GOBB GOBB GOBB GOBB GOBB GOBB GOBB GOB GO	000000 000000 000000 000000 000000 021251 0521251 000000 000000 000000	04C000 04C000 04C000 040000 040000 164C56 057415 163776 037124 C37124 C37124 G27124	000000 000000 000377 000777 000777 000777 000777 000377 000000 000000	000000 000000 176525 165253 165253 165253 165253 176525 000000 000000	C4CO CP C4CO CP C4CO CP 113753 C27742 C27742 C27743 C27743 C41544 C41544 G41544
0 512 1724 512 1024 512 1024 -512 -1024 -512 -1024 -512	04000m 04000m 04000m 037776 077776 037776 037776 037776 040000 040000	000000 0000000 0000000 0000000 0000000 0000	27555 237555 237555 164742 154554 111075 104341 111062 154437 164605 037321 037321	200000 000000 000000 000000 177400 177400 177400 000000 000000 000000 000000	000000 000000 000000 000000 021251 052521 021251 000000 000000 000000 000000	037124 037124 037124 037124 037124 163207 047553 163130 036253 036253 036253	00000 00000 00000 000377 000777 000777 000777 000777 000377 000377 000000 000000 000000	00000 00000 176525 165753 165753 165753 165753 176525 00000 00000	041544 041544 041544 115512 031500 031500 031500 031500 116377 043303 043303
512 1024 512 1024 512 1024 512 -512 -1024 -512 -1024 -1024	040000 040000 040000 037776 037766 037766 037766 037770 040000 040000	000000 000000 000000 000000 000000 00000	C37321 C27321 C27321 164475 1643C4 110617 104C55 16604 164175 1643-2 G37105 C37105	00000 00000 00000 00000 00000 177400 177400 177400 00000 000000	000000 000000 000000 000000 000000 021251 052521 000000 0000000 000000	036 253 036 253 036 253 036 253 162336 046 703 16256 035401 035401 035401 035401	000000 000000 000000 000777 000777 000777 000777 000777 000777 000000	00000 00000 00000 176525 165253 165253 165253 165253 176525 000000 000000	043303 043303 0433247 117247 033233 033233 033233 033233 120127 045043 045043
1024 1024 1024 1024 1024 -512 -1024 -512 -1024 -512	040000 040000 037776 037776 037766 037776 037777 037777 040000 040000	0.0000 r C C C C C C C C C C C C C C C C C	C2710F C3710F C3710F C27105 164242 164232 11033F 103564 110322 15371F 164112 036657 C36657	ccccc clcccc cccccc cccccc cccccc 177450 177450 cccccc cccccc cccccc cccccc cccccc	COGGGG CCCCCC CCCCCC CCCCCC CCCCCC CCCCCC CCCC	07=401 03=401 07=401 07=401 161466 04=037 161406 034526 034526 034526 034526	6CBCCP 6CCCCP 9CCGGA7 9CCG777 9CC777 9CC777 9CC777 9CC777 9CC777 9CC777 9CC777 9CC777 9CC777 9CC777	666°CC 666°CC 676°CC 176°CC 165°753 165°753 165°753 165°753 175°753 175°753 176°CC 660°CC 660°CC	C45042 C45042 C45042 121000 034771 034771 034771 034771 121665 C46600 C46600

512 1024 512 1024 512 1024 -512 -1024 -312 -1024 -512	040000 040000 040000 027777 037770 037766 037766 037776 037776 040000 040000	000000 000000 000002 000052 000155 000155 000155 000155 000000 000000 000000	G3A657 C3A657 C3A657 16400 163544 110044 10325 110031 167426 163643 036426 C36426	000000 000000 000000 000000 177400 177400 177400 000000 000000 000000	COOCOC CCOCCC GOOCCC COOCCC COOCCC GOOCCC GOOCCC GOOCCC GOOCCC GOOCCC GOOCCC GOOCCC	C34526 L34526 C34526 C34526 C34526 160520 C45173 160540 C35653 L33653 C33653	066C06 0C0000° 0G0000° 0G0377 0G0777 0G0777 0G0777 0G0777 0G0377 0G0377	000000 000000 000000 176-25 165253 165253 165253 165253 176525 000000	C466 CC C466 CC C466 CC 122537 C36521 C36521 C36521 C36521 C36521 C36521 C36521 C36521
512 1524 512 1624 512 1628 -512 -1024 -512 -1024 -512	74 770 74 7776 77776 77776 77776 77776 77776 77776 77776 77777 7777 7777 7777 7777 7777 7777 7777	0800000 000000000000000000000000000000	C35425 C35425 C35425 1G3533 1G3264 1O7532 1C2765 1C7547 163131 16314C4 C3520C C352CO	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	800000 000000 000000 000000 021251 052521 021271 000000 000000 000000	073653 037653 037653 033653 157753 044326 157673 033002 033002 033002	000000 000000 000000 000377 000777 000777 000777 000777 000000 000000	000000 000000 000000 16525 165253 165253 165253 165253 165253 16525 000000 000000	750337 750337 750337 750337 740251 740251 740251 740251 740251 752077 752077 752077
1024 512 1024 512 1024 -512 -512 -1024 -712 -1024 -712	C400CC C400CC 040CC 047776 C77777 C37766 C37766 C37776 C37776 C37777 C37776 C400CC C400CC	Consor consor consor consor consor consor consor consor consor consor consor consor consor consor consor consor consor consor	C36200 C36201 C36203 163273 163003 107272 107465 107256 157655 163104 C35754 C35754	60000C 60000C 60000C 6000C 17740C 17740C 17740C 00000 CCCOCC 00000C 00000C	000000 000000 000000 000000 001251 002521 021251 000000 000000 0000000000	033002 037002 037002 033002 033002 157103 043461 157023 032130 07213L 03213L 03213L 03213L	000000 000000 000000 000000 000000 00000	GBBrGG 000700 000700 176525 165253 165253 165253 165253 176525 000700 000700	C5207- C5237- C5237- 176025- C420A4 C420C4 C420C4 C420C4 C420C4 1767- C73625- C53625- C53625-
1024 512 1024 1024 112 1024 112 -1512 -1024 -512	547070 540707 637776 637776 637776 637777 637777 637777 640000 640000 640000	000000 100000 100000 100000 100000 100000 100000 100000 100000	C35754 C35754 C35754 L35754 167525 1C7CG7 1C2175 LA6775 1,7415 162746 C3554C C3554C	060000 060000 000000 000000 1774UC 177600 17742C UUDDOO 040000 000000 0000000	000000 00000 00000 00000 00000 00000 0000	037130 037131 037130 032130 032130 157033 64761b 157152 031256 031256 031256	368000 300000 300000 300377 600777 900777 900777 900377 900377 900300 90000000000	005700 003700 003700 175425 165753 165753 165753 165753 176425 000700 070700	C 53 67 7 7 7 53 67 7 7 1 3 5 3 7 7 1 4 3 5 3 7 7 1 4 3 5 3 7 7 1 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 3 5 6 7 5 5 5 3 5 6 7 5 5 5 6 7 5 5 3 5 6 7 5 5 5 6 7 5 5 5 6 7 5 5 6 7 5

Three Axis - Runs 5-8
TABLE 5.3 (cont.)

0 512 1024 512 1024 512 1024 -512 -1024 -512 -1024 -512	740000 640000 640000 637776 637776 637776 677776 677776 640000 640000	00000n 00000n 000000 000000 000155 000155 000155 000000 000000 000000 000000	035540 035540 162572 162246 106522 101677 106507 162135 162446 035314 035314	00000 00000 00000 00000 00000 177400 177400 00000 00000 00000	00000 00000 00000 00000 00000 021251 052521 621251 00000 00000 00000 00000	031256 031256 031256 031256 031256 155364 041750 155304 037403 037403 037403 037403	000000 060000 000377 000777 000777 000777 000777 000777 000777 000777 000000	00000 00000 175725 165753 165753 165753 165753 176725 00000	755356 753356 753356 131306 045256 045256 045256 045256 145256 132167 757106 057106
512 1024 512 1024 512 1024 -512 -1024 -512 -1024 -512	04 9000 040000 027776 037766 037766 037766 037776 037776 037776 040000	TOCOOT 107 307 107 107 100 107	C35314 C35314 C15314 162336 161777 166235 101406 107422 161664 162203 C35061 C35061	0000CC 0000CC 0000CC 0000CC 0000CC 1774CC 1774CC 0000CC 0000CC 0000CC	000000 00000 00000 00000 00000 00000 0000	030403 030403 030403 030403 030403 154512 041101 154432 027530 027530 027530 027530	000000 000000 000000 000377 000777 000777 000777 000777 000377 000377 000000 000000	000000 000000 000000 176-25 165-253 165-253 165-253 165-25 165-25 000000 000000	057105 057105 057105 057105 047000 047000 047000 047000 133717 060640 060640

Three Axis - Runs 9 and 10 TABLE 5.3 (cont.)

BFOR.IS JUPITR CYCLE DON COMPILED BY 1201 00570 ON 27 FEB 70 AT 10:48:52.

MAIN SHORRAM

STOTAGE USED: CODE(1) OCYCLS: DATA(0) COCC42: BLANK COMMOR(2) COCC03

0001	rr275 1rcL	crei	273773	1 2 L	ርሶር1	000110	150C	0001	000172	1560	0001	0,613#	164C
וייין	CCC141 1710	ርበሮ 1	505,77	1566	1393	000277	349L	0001	700154	3000	0001	BCC273	SLCF
רכנו	200475 290L		600375	ŽaSL	COCL	696471	300L	0001	000355	3026	6001	000463	3 1 3 C
2001	P02445 3260		C00454	3326	1333	000463	3360	0001	PBG502	350G	0001	000473	3 < 0 L
noci	CCCC74 4356		600715		2001	000756	461C	0001	000763	4656	6001	000770	971G
רפרו	222546 49DE		000706	499L	CPC1	000702	STOL	0001	000796	59 C L	onci	000774	REGL
ccri	TOTOCO KECK		LCCCSS	••	(000	CCCC26	820CE	1000	068241	9G L	១៣០៥	000027	PLCCE
	101023 9101	F COUC	000032	72 CDF	(100	I 000004	C 1 1	0000	I 000007	C12	I מחמט	30012	C 13
	xo topona j		1 000002	24	១០៨០	1 000003	D 2	0000	1 200015	IN		200721	_
	ו בשמתפת	0000	1 000024	ĸ	0 00 0	I 000023	Le	0000	ציפרסס ז	LIĦ		317006	
	202017 1742	2003	1 300020	L I 4 3	0000	1 000000	OUT	0002	ם מספפת ז	PΑ	0002 I	าวกาอเ	7

Main Program

TABLE 5.4

Program Listing

```
200 FCRMST(141)
          9 a
00117
CC11?
          10 -
                - 101 FC=MAT(/)
CLIIL
          11*
                       CLT = 0
nolle
          17+
                       IN 25
          15*
20118
                1 >
                       READITATED CX FOY FOO
32123
          14 *
                       IF(CX.EQ.-1) STCP
LCI JE
          15 *
                       AFITE (SUTIFFICE) EXIPYILI
00132
          15+
                       7845 (IM +9200) PRILITIFETHURETY7
00140
          17*
                       WRITE(GUT+820G) PR+LIG1+LIML+LIM7
00145
          1 2 *
                        READ(IN. CIDD) C11
reira
          15 *
                        PEAC(IN: 9100) Cla
00152
          20 4
                       READ(IN+8100) 013
00170
          21 *
                       DC 7CC LINE1+LIN3
        52*
ng173
                       L3≃C
          27+
00176
                       2=1
          _ + ^
2 ~ *
20175
                       WRITE(0UT+2020) [3+011+012+013
92214
                       00 350 K=1+LIM2
                       LEEK*7
00217
          7= =
20230
          27 4
                       IF(EX.ES.3) 60T0 199
          2 c *
00222
                       00 100 J=1+LIM1
          27*
10275
                       CALL ITEP(C12.C13)
د څه د
                        IF((LIM1.E0.1) .ARE. (MCC(MAFF).F6.C1) 3670 97
          3-+
0237-
                       15( "C0(U.FR),NE.D) C0T0 10L
          314
78277
          32 *
                       LEEJ-7
00277
          33 *
                ၁င
                       *RITE(CUT,9000) Lo.011.012.013
90252
          34 •
                177
                        SUPLITACS
00254
                       IF (CY.EG.C) GOTC 299
          35 *
                150
22236
          354
                       30 307 J=1+LEM1
12221
          37+
                       CALL ITER(C17,C11)
                        IF((CLI41.F9.1) .WMS. (MOD(K.PT).FW.G)) DOTO 137 IF(MOD(W.FF).NE.C) COTO DEG
12232
          3 ₹ *
CC2F4
          31×
20255
          4 T *
                       しピニリ* 7
                       WRITE(CUT.ªCCG) La.C11.C12.C13
          41=
20067
                150
                        SCNTIMUS
25325
          47 *
                 270
20012
                 7 5 5
                        IF(07.50.6) 3010 350
          43 *
                       po dem Delablini
20012
          44.
20315
          45*
                        CALL ITER(C:1:C1.)
                        IF((LIM1.E0.1) .AND. (MCJ(K.07).FJ.5)) 5073 295
10015
          45*
75377
          47*
                       IF (MOD(J.FR).NE.E) RUTO 300
-- 3--
          47*
                       1,423*7
00-202
                - ,-
                       WRITE(OUT, OFDE) La + 011+ 212+211
          49+
                 377
20245
          5~*
                        CONTINUE
22344
                        SUNTINCE
          51.
00345
          57*
                        1=-1
                        IC PEC K=1+FIMS
26347
          E 3 *
25352
          54 *
                       しろこくゃつ
25.2
                        IF(02.F9.C) COIN DEN
          55 +
          5€*
7_35=
                        CO 40T UTI+LIMI
nēzan
          27*
                        CALL ITET (C11:C12)
                        IF((LIM1.FG.1) .AND. (MOD(K.PF).FG.D)) GOTO 3°D
          54*
25351
                        [F() 00(J.PP).NE.C) 6010 400
r:3327
          36*
          67*
10355
                       F3=3*7
ngger
          £ ; *
                 7:-
                       _AAITE(0UT+9600) L_+011+012+012
12475
                 437
                        BUPLITACE
          52 +
```

Main Program (cont.)

```
220
22427
          53*
                       IF(IY, 2000) COTO 495
                        1/(1/1032) 1/10 1/20

3/( 100 U=1+L IM1

CALL ITEP(C13+C11)

IF((LIM1.F9.1) .AND. (403(K+P ).7..0)) 00TO 437
70-11
70414
          54 *
          85 *
          ē£∗
00415
r('417
          67 =
                        IF() 00(U.PT). NE. 0) COTC STC
uC+31
          5 g *
                        しうこよまで
                 450
00422
          63*
                        WRITE(CUT+2000) La+011+012+013
C2441
          70 *
                 500
                        CONTINUE
                        IF(CX.EQ.C) 8010 650
00443
          71 *
                 499
                        CC445
          72*
00450
          73*
                        CALL ITERICIZ:013)
00451
          74 =
                        IF((LIM1.Eq.1) .ANG. (MOD(K.PP).F..()) 30TO 59T
                        IF(MCC(U.PR).AE.O) 1010 60.
L-=U*7
רים 4 בֿ ג
          75*
7545E
          7F *
                 - 3-
          77+
                        #FITT(SUT+9896) L5+611+613+713
                 -:-
55425
          7 . *
                        SUNTIAGE
                 5~
92477
          72-
                        CONTINUE
00501
          d€≇
                        WPITE(OUT:920E)
00573
00575
                 7 --
                        CONTITUE
          51 *
          ٠;٠
                        30TU 10
00515
          ₹2.
                        E N D
        IND OF COMPILATION:
```

Main Program (cont.)

. PUTTZCPBAIL GA

```
BEOD. IT MART
CYCLF FOR COMPTERS IN 12 1 COSTO ON 37 FEB 70 AT 16:40:50.
                        INT Y POINT CO0312
   SU COUTINE ITES
  STORAGE MSED: CORE(1) COC370. DATA(0) GCOC61: RLANK COMMON(2) GCOC63
  EXTERNAL DEFERENCES (BLOCK + NAME)
   0000
           SCALE
   0004
           NE RO34
  STORAGE ASSIGNMENT (BLOCK+ TYPE+ RILATIVE LOCATION+ NAME)
          000035 9000F
   סמסס
                            0000 I D00010 IEC
                                                    COLD I GDOCCS IES
                                                                             0000 I OCCC?6 IFC
                                                                                                     0000 1 000023 IFS
   repo I neoc25 Tec
                            DOCO I 000022 IGS
                                                    CCGO I COCC24 IHC
                                                                             0000 I COCC21 IFS
                                                                                                     onen I meness Isc
   0000 I 000027 IJS
                            0000 I 000033 IKC
                                                    0000 I 000030 IKS
                                                                             0000 I 000034 ILC
                                                                                                     0000 I 000031 ILS
   0000
         Z9LNI 0#0000
                            0000 I 000011 IRC
                                                    0000 I 000006 IRS
                                                                             0000 I 000012 IYC
                                                                                                     0000 I 000007 IYS
   U 200000 I 2000
                            COOD I DODDIE JEC
                                                    LOCO I DODOLI3 JES
                                                                             0000 1 000017 JRC
                                                                                                     236 #10000 1 0000
   pose I openso hic
                            DCDG I DODD15 JVS
                                                    0000 I 000002 AM
                                                                             Q000 I 0000°3 HN
                                                                                                     SH EBOODD I DOOD
   0000 I 00000 NH
                           ี เออออ์ รั ออออออ งบร
                                                    0002 I 000000 PR
                                                                             0002 I 000001 Z
```

Subroutine ITER (performs one iteration on two direction cosines)

```
20101
                        SUBPOUTINE ITERIC.CY)
   22103
             ? •
                         INTEGER PRIZIDICICY OF
             7.
   00104
                         DIMENTION C(3)+CY(3)
   00105
                        COMION PD.7.J
SATA 57/22769/348/655 /3: N/FESCE/1 4/65534/
   20166
             ٠.
   00113
                         34T# CJT/6/
             3 ¢
                  -: CF FCP AF(IIP+6(4X+05))
   CCIIE
             7+
   0311F
                         180:0031
             3 *
   00117
            3+
1^+
                         IRS-C(2)
   00120
                         :YS=C(1)
   00121
            11.
                         IECHCY(3)
   00122
            12=
                         IRC=CY(2)
   00123
            13=
                        IYC=CY(1)
   00174
            14 *
                         JES: [ES/MC
   08125
            15.
                         JRS=IRS/MD
           1 ~ •
   DC12F
                        JYS= IYS/40
   00127
            17*
                        JEC-IFC/40
   00130
            } + +
                        JEC=IEC/MC
            14.
                         JYC:IYC/M3
   00131
   00135
            ::•
                         IHS=IES-IYS-JRS
                     , IDS:128-MA-JYS
   C133
            21 *
                        IF5:14"-" + J4
   CG134
            20135
            23•
                        IHC*IFC-TYC-JPC
   77175
77177
                         ISC-1FC-M1+016
            24+
                        IFC IVC-WARJYL
            · 5*
                        145:1:150:4150
145:1:17
  CClr
            ٠ ٠
   77141
             7 *
  r-14-
                         00143
             25.
                           IJC=2*IRS*JES
  00144
             35*
                           IKC=2*IYG
   10145
             21*
                           ILC=Wu*JAZ
                           CALL SCALE (IFS. IT . IF )
CALL SCALE (IFC. ITU. IF.)
  P0146
             32*
1 0147
             33.
  OCIEC
                          CALL SCALETIFC+IKT+IA )
             34 *
  00151
             25=
  66125
             3 - +
                           IES= [474] JC #7
  00153
             27*
                           IRS=IRS+IKC+7
  CG1=4
             : · ·
                          I45=IF5+1LC+~
  00155
             3 .
                          IEC=I+C-IJC*7
  09155
             4.74
                           IRC=ICC-IKC+Z
  20157
             41 *
                           IYC=IFC-ILC*Z
  დე1 იი
             47*
                           CALL SCALF(IYS+TRI+Ic.)
  20151
             ų~+
                           CALL SCALE(IYU: IPC: TEU)
                           JRS=IRS/MC
  21152
             44 *
                           JAZ=IA2/AC
  00153
             45*
  00174
             454
                           JFC=IFC/MC
  00155
             → 7 *
                           JACTIAC\AU
  20155
             4.74
                           C(3)=IES-IYS-UPS
             4 *
  CCFF7
                           C(T)=IRS-MM+UYS
  20172
             J^.
                           YU*M5-243=(1)C
  75171
             51+
                           CY(3)=IEC-IYC-UFC
  00172
             57*
                           CY(2)=IRC-MN+JYC
  90177
             57*
                           CY(1)=IYC-MN+JYC
                           CALL FCALE(C(1)+C(1)+C(5))
CALL FCALE(CY(1)+CY(2)+CY(3))
  90174
             54.
            55 *
  20175
             F : 4
  22175
                           RETUPN
  00177
             Ε7≖
                           END
          THO OF COMPILATION:
                                          NO LIAGICSTIC .
```

Subroutine ITER (cont.)

REPORTS NEPTUN CYCLE DOG COMPILED BY 1201 DOSTO ON 27 FEB 70 AT 10:49:59.

SUBROUTINE SCALE ENTRY POINT COULS

STORAGE USED: CODE(1) DODIEG: DATA(D) DODDOT: BLANK COMMON(2) DODDDO

EXTERNAL REFERENCES (BLOCK | NAME)

DD03 NERR35

STORAGE ASSIGNMENT (oLOCK, TYPE, RELATIVE LOCATION, NAME)

 DDD1
 DDD001
 1CL
 สีมัติ
 BD0015
 1DCL

 DD01
 DD0001
 X
 DD0001
 DD0005
 QUO

 DD01
 DD0001
 X
 DD0000
 Y
 DD00000
 HM

0001 - 000030 200L

0001 000110 6001

0003 : 98

Subroutine SCALE

(scales one direction cosine by operating on each of the three integer parts)

```
SUBROUTINE SCALE(11:12:13)
80101
           10
                       DATA NR/855364-
00103
           2*
00105
           3 *
                       K=0
                 10
                       IF(13.LT.HH) GOTO 100.
00106
           4.
                        13=13-KH
           5.
00110
00111
           €+
                        K≃K+1
                        CO TO 10
00112
           7*
                        IF( 13.9E.D) 60T0 200
00113
           6 *
                 100
           9 *
00115
          10+
                        K=K-I
00116
                        SCT 0 100
          11*
CC117
                 200
                        I2=I2+K
00120
          12=
          13.
00121
                        K =₽
                       IF(12.LT.HP) COTO 300
I7=12-PM
00172
          14 -
                 219
00154
          15*
                        K=K+1
00125
          15*
                        SCTS 210
C0126
          17.
                        IF(12.62.0) GOTO 403
12=12+88
          13*
15*
                 300
00127
00131
                        K=K-1
GOTC 300
20135
           20 =
20173
           21 *
00134
           27*
                 400
                        11=11+K
          23*
                        KEC
CG135
          24*
                        IF(II.LT.84) 60T0 500
                 419
00136
                        11=11-8M
          25=
0140
                        50TC 410
           26*
00141
                        IF(I1.52.0) 3010 400
 25147
           27.
                 597
          23.
                        11=11+MP
3313 =33
~C1 u u
 22145
                        11=1485(11) .
 JOIUE
                        12=1483(12)
00147
                        13=1450(12)
 22157
           • 7د
                        ·_Tu^* + _
 20151
          . 3 •
```

Subroutine SCALE (cont.)

APPENDIX A

SMOOTH PULSE SEQUENCES (SRRC-RR-68-48)

SMOOTH PULSE SEQUENCES

A. J. Lincoln, M. Cohn and S. Even Sperry Rand Research Center, Sudbury, Massachusetts

INTRODUCTION

The necessity sometimes arises in digital systems to generate external pulse rates whose frequency is related to the internal clock frequency by some proper rational fraction while still maintaining synchronism with the internal clock source. In many such cases, it is a requirement that pulses of the generated frequency be as uniformly spaced as possible within the constraint of synchronism. We define such pulse sequences as smooth pulse sequences in contrast with uniform sequences in which each pulse is separated from its predecessor by a fixed interval. The smooth sequences possess a number of interesting properties, both in their structure and in the ways they can be generated. Some of these properties will be treated in the following discussion.

Although it has not, to the authors' knowledge, been previously identified as such, a method has been in use for some time for generating smooth sequences. This is the constant multiplier used in digital differential analyzers (DDA's). Another technique often used for forming synchronous frequency multiples uses the "rate multiplier," and involves detecting the one-to-zero transitions of the stages of a binary counter chain. The rate multiplier technique, although capable of forming relatively smooth sequences, does not form a true smooth sequence, as can be easily demonstrated.

Other methods for generating smooth sequences can be described.

Our interest here, however, is to provide a formal foundation for the subject and to prove several important properties of smooth pulse sequences.

PROPERTIES OF SMOOTH SEQUENCES

Choosing an arbitrary reference point in time, and assuming, for convenience, a unit-period clock, we define two types of pulse sequences: Uniform Sequences and Smooth Sequences. Each can be described by a doubly-infinite sequence of real numbers, the ith number giving the arrival time, as counted by the clock, of the ith pulse. Since our reference-time zero and the position of the index zero can be chosen arbitrarily and independently, we wish to consider equivalent those sequences which differ only by a shift in time or by reindexing. In other words, only the "pattern" of a sequence is important. Accordingly, we first make the following definition:

Definition 1:

Two arrival-time sequences $\{a_{\underline{1}}\}$ and $\{b_{\underline{1}}\}$ are $\underline{equivalent}$ if for some integers t and τ ,

$$a_i = b_{i+\tau} + t$$
 , $-\infty \le i \le \infty$.

A uniform pulse sequence is an ideally smooth sequence with rate p/q times that of the clock. It consists of p uniformly spaced pulses during every q clock periods.

Definition 2:

A <u>Uniform Pulse Sequence</u> of rate p/q has pulses at times $\{u_1\}$, where $u_i=i\frac{q}{p}, -\infty \le i \le \infty$.

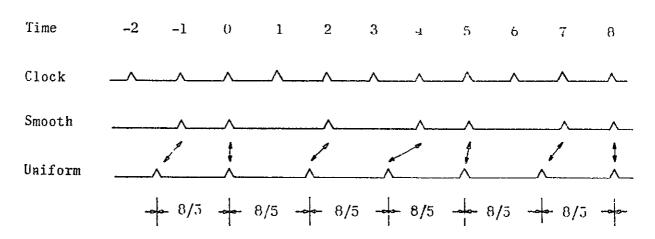
Unless q/p is an integer, the pulses of the uniform sequence do not all coincide in time with clock pulses, so the problem of synchronous pulse rate generation cannot generally be solved by a uniform sequence. The concept, though, is crucial in defining and characterizing smooth sequences, which, heuristically, are the best synchronous approximation to uniform sequences.

Definition 3:

A Smooth Pulse Sequence of rate p/q has pulses only at integral clock times $\{s_i\}$, $-\infty \le i \le \infty$; moreover, these pulses can be put into one-to-one correspondence with the pulses of the uniform sequence in such a way that $\max_i (s_i - u_i) - \min_i (s_i - u_i) \le 1.$

To construct a concrete example of a smooth pulse sequence for the fraction 5/8, we place pulses at those clock times which coincide with or immediately follow pulses of the uniform sequence.

Example 1



Here the arrival times of the smooth sequence are $1, \dots, -1, 0, 2, 4, 5, 7, 8, \dots$. If the pulse pattern between, say, time 0 through time 7 is

repeated indefinitely, an infinite, smooth sequence of rate 5/8 results. Since this sequence was constructed to be periodic, it suffices to observe the smoothness of a single period. Under the natural correspondence (shown by arrows), the deviations between the smooth and the uniform arrival times range between 0 and 4/5, satisfying Definition 3.

The last condition in Definition 3 bounds the range of time deviations between pulses of a smooth sequence and their correspondents in a uniform sequence. We next observe that the bound can be sharpened and that within the equivalence relation the deviations themselves can be bounded.

Since the s_i are integers, and the u_i are integral multiples of q/p, the differences (s_i-u_i) between corresponding pulse times must be integral multiples of 1/p, hence

<u>Lemma 1</u>: A smooth sequence satisfies the inequality

$$\max_{i}(s_{i}-u_{i}) - \min_{i}(s_{i}-u_{i}) \le \frac{p-1}{p}$$
.

Now suppose that i_0 is an index where the difference (s_1-u_1) achieves its minimum; † that is,

$$\min_{i}(s_1-u_i) = (s_{i_0}-u_{i_0})$$
.

By an integral shift in time and a reindexing, we form the new sequence $\{s_1'\}$, where

$$s_{i}' = s_{i+i_0} - s_{i_0}$$
.

To be rigorous here we should note that Lemma 1 and its preceding discussion imply that the differences (s_-u_i) take on at most p distinct values, and that these values are bounded below by $s_j-u_j-(p-1)/p,$ where j is an index chosen arbitrarily. Therefore, the sequence has a greatest lower bound, which is s_i-u_i for some i_0 .

The minimum deviation of $\{s_i'\}$ from the uniform sequence is given by

$$\min_{i}(s_{i}'-u_{i}) = \min_{i}(s_{i+i_{0}}-s_{i_{0}}-u_{i})$$

$$= \min_{i}(s_{i+i_{0}}-u_{1}-u_{i_{0}}-s_{i_{0}}+u_{1_{0}})$$

$$= \min_{i}(s_{i+i_{0}}-u_{i+i_{0}}) - (s_{i_{0}}-u_{i_{0}}) .$$

But by definition of i_0 this quantity vanishes, so that all deviations of $\{s_i'\}$ from the uniform must be nonnegative. Invoking Lemma 1, we can now state:

<u>Lemma 2</u>: Within equivalence, every smooth sequence satisfies $0 \le (s_1^{-u}) \le \frac{p-1}{p} , -\infty \le i \le \infty .$

The sequence in Example 1 was designed to satisfy this bound without an equivalence transformation.

We are now able to prove the fundamental theorem of smooth sequences.

Theorem 1: A smooth sequence of rate p/q is unique to within equivalence.

<u>Proof</u>: Given any two smooth sequences of rate p/q, consider their equivalent forms complying with Lemma 2. The i^{th} pulses of both smooth sequences must coincide with clock pulses, and must coincide with, or lag by less than a clock period, the same correspondent, u_1 , in the uniform sequence of rate p/q. Therefore, the i^{th} pulses in the two smooth sequences must coincide with the same clock pulse, hence with each other.

This is an extremely strong result, following, as it does, only from the definitions of uniform and smooth sequences and the notion of equivalence.

So far we have used arrival times to describe pulse sequences. It is convenient now to introduce a dual description, the cumulative count. If A(t) is the number of pulses in the sequence $\{a_i\}$ which have arrived by time t, we define the "count sequence" $\{\alpha(t)\}$, where

$$\alpha(t) = A(t) - A(a_0) .$$

Thus $\alpha(t)$ is an integer-valued function of time, satisfying

Lemma 3: If $\{a_i\}$ and $\{\alpha(j)\}$ are, respectively, the arrival time sequence and the count sequence for a synchronous pulse sequence.

$$\alpha(j) = 1$$
 for $a_i \le j < a_{i+1}$

$$a_{\alpha(j)} \le j < a_{\gamma(j)+1}$$

As done in Lemma 3, we will always use the lowercase Greek equivalent of the arrival-time character for the corresponding count sequence. Also, by analogy with the notation $\{u_i\}$ for the arrival times of pulses in the uniform sequence, we make the following definition.

Definition 4. A uniform sequence of rate p/q has a (rational) count sequence $\{\upsilon(\jmath)\}$, where

$$\upsilon(j) = j \frac{p}{q}$$
 , $-\infty \le j \le \infty$.

We are now ready to prove the important relationship between the arrival time sequence and the count sequence.

Theorem 2 (Duality Theorem):

If $\{a_{\underline{i}}\}$ and $\{\alpha(\underline{j})\}$ describe a synchronous pulse sequence of rate $\frac{p}{q}$,

$$\max_{\mathbf{i}}(\mathbf{a_i} - \mathbf{u_i}) - \min_{\mathbf{i}}(\mathbf{a_i} - \mathbf{u_i}) \leq \frac{p-1}{p}$$

if and only if

$$\max_{J} (\upsilon(j) - \alpha(j)) - \min_{J} (\upsilon(j) - \alpha(j)) \le \frac{q-1}{q}$$

 \underline{Proof} : To prove the "if" part, observe that for any a_i ,

$$\frac{q}{p} \min_{j} (\upsilon(j) - \alpha(j)) = \frac{q}{p} \min_{j} \left(\frac{p}{q} \, J - \alpha(j) \right) \le \frac{q}{p} \left(\frac{p}{q} \, a_{i} - \alpha(a_{i}) \right) = (a_{i} - u_{i}) .$$

Also, since

$$\frac{q}{p} \max_{\mathbf{j}} (\upsilon(\mathbf{j}) - \alpha(\mathbf{j})) \ge \frac{q}{p} \left(\frac{p}{q} \left(\mathbf{a_i} - 1 \right) - \alpha(\mathbf{a_i} - 1) \right) = \left(\mathbf{a_i} - 1 - \frac{q}{p} \left(\mathbf{i} - 1 \right) \right) ,$$

$$\left(1-\frac{q}{p}\right)+\frac{q}{p}\max_{j}(\upsilon(j)-\alpha(j)) \geq (a_1-u_j)$$
.

From these two results.

$$\left(1-\frac{q}{p}\right)+\frac{q}{p}\max_{j}(\upsilon(j)-\alpha(j)) \geq \max_{i}(a_{i}-u_{i})$$
,

$$\frac{q}{p} \min_{j} (\upsilon(j) - \alpha(j)) \leq \min_{i} (a_{i} - u_{i}).$$

By subtraction and hypothesis,

$$\left(1 - \frac{q}{p}\right) + \frac{q}{p}\left(\frac{q-1}{q}\right) = \frac{p-1}{p} \ge \max_{i}(a_i - u_i) - \min_{i}(a_i - u_i)$$

To prove the "only if" part, observe that for any clock time j , there is a pair of successive arrival times such that $a_1 \le j \le a_{i+1}-1$, so that $\alpha(j)=i$. Therefore,

$$\frac{p}{q} a_{i} - i \leq \frac{p}{q} J - \alpha(J) \leq \frac{p}{q} (a_{i+1} - 1) - i ,$$

$$\frac{p}{q} (a_{1} - u_{1}) \leq \nu(J) - \alpha(J) \leq \frac{p}{q} (a_{i+1} - u_{1+1}) - \frac{p}{q} + 1 .$$

But then

$$\left(1 - \frac{p}{q}\right) + \frac{p}{q} \max_{\mathbf{i}} (\mathbf{a}_{\mathbf{1}+\mathbf{1}} - \mathbf{u}_{\mathbf{1}+\mathbf{1}}) \geq \max_{\mathbf{j}} (\mathbf{v}(\mathbf{j}) - \alpha(\mathbf{j})) ,$$

$$\frac{p}{q} \min_{\mathbf{i}} (\mathbf{a}_{\mathbf{i}} - \mathbf{u}_{\mathbf{i}}) \leq \min_{\mathbf{j}} (\mathbf{v}(\mathbf{j}) - \alpha(\mathbf{j})) ;$$

again by subtraction and hypothesis,

$$\left(1 - \frac{p}{q}\right) + \frac{p}{q}\left(\frac{p-1}{p}\right) = \frac{q-1}{q} \ge \max_{\mathbf{j}} (\upsilon(\mathbf{j}) - \alpha(\mathbf{j})) - \min_{\mathbf{j}} (\upsilon(\mathbf{j}) - \alpha(\mathbf{j})) .$$
 QED

An obvious consequence of Theorem 2 and Definition 3 is

Corollary 2.1: A synchronous pulse sequence described by the count sequence $\{\alpha(j)\}$ is smooth if and only if .

$$\max_{j} (\upsilon(j) - \alpha(j)) - \min_{j} (\upsilon(j) - \alpha(j)) \le \frac{q-1}{q}.$$

In the discussion which follows, several of the results have analogous statements and analogous proofs in terms of arrival times as well as count sequences. In such cases, both statements, but only one proof, will be given.

Lemma 3: If, for all i, $a_{i+c} = a_i + d$, then for any integer k,

$$a_{1+kc} = a_1 + kd$$
.

Lemma 3': If, for all j, $\alpha(j+d) = \alpha(j) + c$, then for any integer k.

$$\alpha(j + kd) = \alpha(j) + kc.$$

<u>Proofs</u>: Both proofs are simple inductions on k.

Lemma 1: If, for all 1, $a_{i+c_1} = a_i + d_1$ and $a_{i+c_2} = a_i + d_2$

then $c_1/c_2 = d_1/d_2$

Lemma 4'. . If, for all j , $\alpha(j+d_1)=\alpha(j)+c_1$ and $\alpha(j+d_2)=\alpha(j)+c_2$ then $c_1/c_2=d_1/d_2 \ .$

<u>Proofs</u>: Consider $\alpha(j+d_1d_2)$; applying Lemma 3' twice,

$$\alpha(J) + d_1c_2 = \alpha(J) + d_2 + c_1$$

for all j , so that

$$c_1/c_2 = d_1/d_2.$$

Lemma 5: The arrival time sequence $\{s_1\}$ for a smooth sequence of rate $\frac{p'}{q'} = \frac{rp}{rq}$, p and q relatively prime, satisfies $s_{1+p} = s_1 + q$ for all 1.

Lemma 5': The count sequence $\{\sigma(j)\}$ for a smooth sequence of rate $\frac{p'}{q'} = \frac{rp}{rq} \ , \ p \ \text{ and } \ q \ \text{ relatively prime, satisfies}$ $\sigma(j+q) = \sigma(j) + p \quad \text{for all} \quad j \ .$

Proofs:
$$\sigma(j+q) - \sigma(j) = \sigma(j+q) - \upsilon(j+q) - \sigma(j) + \upsilon(j) + q \frac{p'}{q'}$$
$$= \{\sigma(j+q) - \upsilon(j+q) - \sigma(j) + \upsilon(j)\} + p.$$

The difference on the left-hand side of this equation is clearly an integer, while the bracketed quantity on the right is less than unity (by Cor. 2.1). Therefore, the bracketed quantity must be zero, proving the lemma.

We now define two new sequences, the first differences of the arrival times and the count sequence. The first, called the "gap" sequence, consists of the clock-time intervals between pulses. The second, called the "binary" sequence, is unity at those clock times when pulses are present, and is zero at all others. Thus, it depicts the pattern of the pulse sequence.

Definition 6: The gap sequence is given by

$$g_i = a_i - a_{i-1}, -\infty \le i \le \infty$$
.

Definition 7: The binary sequence is given by

$$\beta(j) = \alpha(j) - \alpha(j-1), -\infty \le j \le \infty$$
.

Theorem 3: A smooth pulse sequence is periodic. If its rate is $\frac{p'}{q'} = \frac{rp}{rq} , p \text{ and } q \text{ relatively prime, then the period}$ is q clock times during which p pulses appear.

Proof:
$$\beta(j+q) - \beta(j) = \sigma(j+q) - \sigma(j+q-1) - \sigma(j) + \sigma(j-1)$$
$$= \sigma(j+q) - \sigma(j) - \sigma(j+q-1) + \sigma(j-1)$$
$$= p - p = 0.$$

Lemma 5' makes explicit the number of pulses in each period, and Lemma 4' proves that if there were a shorter period than q, then p and q could not be relatively prime.

QED

These last results simplify the investigation of smooth sequences in two ways. First, only rates in reduced form, that is, with $\,p\,$ and $\,q\,$ relatively prime, need be considered. Second, a single period suffices to describe any smooth sequence. This permits the use of the following convenient notations for a smooth sequence of rate $\,p/q\,$:

(i) Arrival times:
$$(s_0, s_1, \dots, s_{p-1})$$
;
(ii) Gaps $(g_0, g_1, \dots, g_{p-1})$,
where $g_i = s_i - s_{i-1}$ indices modulo p ;
and $\sum_{i=0}^{p-1} g_i = q$ indices modulo p ;
(iii) Counts $(\sigma(0), \sigma(1), \dots, \sigma(q-1))$;
(iv) Binary $(\beta(0), \beta(1), \dots, \beta(q-1))$,
where $\beta(j) = \sigma(j) - \sigma(j-1)$ indices modulo q .
and $\sum_{j=0}^{q-1} \beta(j) = p$

Finally, we consider the difference-sequences between smooth and uniform sequences.

Lemma 6. The sequence $(s_i - u_i)$ has period q.

<u>Lemma 6'</u>: The sequence $(\upsilon(j)-\sigma(j))$ has period q.

<u>Proofs</u>: Since $u_i = \frac{q}{p}i$, $u_{i+p} = u_i + q$ for all i. By Lemma 5, $\{s_i\}$ satisfies the same recursion, so the difference $(s_i - u_i)$ has a period of q clock times (or p pulses). But since p and q are relatively prime, u_i and $(s_i - u_i)$ are integral only when i is a multiple of p. Therefore $(s_i - u_i)$ has no period less than q.

With this knowledge and the observation that all $(s_1 - u_1)$ are proper fractions with denominator p, and all $(v(j) - \sigma(j))$ are proper fractions with denominator q, we can complete the refinement, begun in Lemmas 1 and 2, of the characterization of smooth sequences.

Theorem 4: A smooth sequence of rate $\frac{p}{q}$ satisfies $\max_{\mathbf{i}}(s_{\mathbf{i}} - u_{\mathbf{i}}) - \min_{\mathbf{i}}(s_{\mathbf{i}} - u_{\mathbf{i}}) = \frac{p-1}{p};$ $\max_{\mathbf{j}}(\upsilon(\mathbf{j}) - \sigma(\mathbf{j})) - \min(\upsilon(\mathbf{j}) - \sigma(\mathbf{j})) = \frac{q-1}{q}.$

<u>Proof:</u> Since the difference $(s_i - u_i)$ periodically assumes p different values, all of which are proper fractions with denominator p ,

$$\max_{i}(s_{i} - u_{i}) - \min_{i}(s_{i} - u_{i}) \ge \frac{p-1}{p}$$

This inequality combined with Definition 3 proves the theorem for the arrival times. A similar argument can be made for the count sequence.

QED

SUMMARY

Starting from a definition of smooth sequences as synchronous pulse trains with bounded range of deviation from an ideal uniform rate, we have seen that the pattern of such a sequence is unique and periodic, and that the deviations from the ideal are quantized and less than unity. Dual descriptions have been given in terms of arrival times and cumulative counts, as well as in terms of their first differences. The deviations of smooth sequences from their uniform counterparts have been characterized.

In closing we note that from the uniqueness of these sequences, which holds even under our rather broad definition of smoothness, it follows that smooth sequences minimize all reasonable measures of deviation from uniform spacing.